

THE PREVENTION OF ELECTRICAL BREAKDOWN  
AND ELECTROSTATIC VOLTAGE PROBLEMS  
IN THE SPACE SHUTTLE AND ITS PAYLOADS

PART I - THEORY AND PHENOMENA

PART II - DESIGN GUIDES AND OPERATIONAL CONSIDERATIONS

ABSTRACT

A two volume manual was prepared that will hopefully prevent workers on the Space Shuttle from having the same sort of problems with electrical discharge phenomena that others in the space program have had. The manual contains an introduction to the theory of corona discharge and electrostatic phenomena. The theory is mainly qualitative so that workers in the field should not have to go outside this manual for an understanding of the relevant phenomena. Some of the problems that may occur with the Space Shuttle in regards to electrical discharge are discussed in the final sections.

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THE PREVENTION OF ELECTRICAL BREAKDOWN  
AND ELECTROSTATIC VOLTAGE PROBLEMS  
IN THE SPACE SHUTTLE AND ITS PAYLOADS

SYNOPSIS

PART I - THEORY AND PHENOMENA

1.0 Introduction.

Throughout the aerospace program high potentials at low gas pressures have caused myriad problems. Many of our scientific satellites have been disabled partially or completely due to electrical breakdown. The genesis of this problem, however, did not occur within the space program. In fact, electrical breakdown of high voltage supplies was a problem in high altitude aircraft during World War II. Also, electrostatic discharge on the surface of the airplane was found to cause many undesirable effects. One of the more important was EMI (electromagnetic interference), and one of the more dramatic was the shattering of the windshield when charge that built up on it suddenly discharged to the metal frame.

Through the years a great deal of experience has been accumulated on how to cope with these problems. Indeed, most of these problems can be eliminated in the design stage. Unfortunately, this experience has not always been communicated to the personnel most in need of it.

This manual is an attempt to help prevent the "rediscovery of the wheel" phenomenon. Most of the electrical breakdown and electrostatic discharge problems that will be faced in the Shuttle have been faced and solved in other efforts.

2.0 Summary of Electrical Breakdown Problems and Electrostatic Voltage Problems

2.1 High Voltage Breakdown Problems

During the period from 1961 to 1968 an inhouse NASA survey was conducted to determine some of the causes of voltage breakdown. The causes were outgassing, entrapped gas, circuit arrangement, inadequate insulation, pressure leak, contamination and environment plasma. It was the conclusion of the authors that most of the problems could be solved in the design stage. However, testing and fabrication practices were also essential.

## 2.2 Electrostatic Voltage Problems

The problem areas with electrostatic discharge have been identified by the workers in the field, e.g. biological shock, fires, premature ignition of electroexplosive devices, mechanical effects, and radio interference. The systems affected have been man, the propulsion system, the ordnance system, the hydraulic system, and the complete range of avionics systems. In recent years, static electricity has also been found to interfere with computers, telemetry, tracking and guidance systems, the sensors employed to acquire scientific data, and thermal control systems.

## 3.0 Phenomena Associated with Electrical Breakdown

This section deals with the qualitative theory of corona discharging and arcing. It is essential to understand this theory before the problems caused by this phenomena can be realistically attacked.

## 4.0 Phenomena Associated with Electrostatic Voltage

This section deals with the qualitative theory of electrostatic discharge. It deals mainly with the effects on rockets and airplanes.

# Part II - Design Guides and Operational Considerations

## 1.0 Introduction

Specific electrical discharge problems can directly affect the Shuttle vehicle and its payloads. General design guidelines are provided to assist flight hardware managers in minimizing these kinds of problems. Specific data are also included on workmanship practices and, most importantly, system testing while in low-pressure environments. Finally, certain electrical discharge problems that may be unique to the design of Shuttle vehicle itself and to its various mission operational modes are discussed.

## 2.0 Design Procedures for the Prevention of Electrical Breakdown in the Space Shuttle and Its Payloads

The first half of this section deals with general design guides: categorizing the different problems and procedures into three peak voltage ranges, designing for breakdown without damage, and including desirable and undesirable soldering, test philosophy, and a design review checklist.

The second half deals with possible electrical breakdown problems with the Space Shuttle and its payloads.

The most serious of the possible problems reviewed occurred during reentry. There seems to be a good chance, unless preventive measures are taken, that the instrumentation wires and the electronics in bays 4, 5, and 6 could be exposed to destructive temperatures and corona effects.

### 3.0 Possible Electrostatic Voltage Problems With the Space Shuttle

This section deals with effects associated with possible changing of the thermal protection system and windshields during launch and reentry including visibility and RF noise as well as possible problems during orbit.

The most serious problem here seems to be the charging of the TPS (tile protection system) during the launch period. These tiles could charge up to such a high potential so as to cause either untenable interference with the data systems or else the destruction of the tiles themselves.

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PART I - THEORY AND PHENOMENA

DISTRIBUTION AND REFERENCING

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*National Aeronautics and Space Administration*  
**LYNDON B. JOHNSON SPACE CENTER**

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PART I - THEORY AND PHENOMENA

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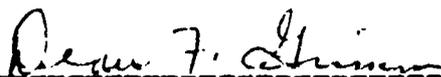
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PART I - THEORY AND PHENOMENA

1.0

INTRODUCTION

Throughout the aerospace program, high potentials at low gas pressures have caused a myriad of problems. Many of our scientific satellites have been disabled either partially or completely as a result of electrical breakdown. The genesis of this problem, however, did not occur within the space program. In fact, electrical breakdown of high-voltage supplies was a problem in high-altitude aircraft during World War II. Also, electrostatic discharge on the surface of the airframe was found to cause many undesirable effects. One of the more important was electromagnetic interference (EMI), and one of the more dramatic examples of it was the shattering of the windshield when the charge that built up on it suddenly discharged to the metal airframe.

Through the years, a great deal of experience has been accumulated on how to cope with these problems. Indeed, most of these problems can be eliminated in the design stage. Unfortunately, this experience has not always been communicated to the personnel most in need of it.

This manual is an attempt to help prevent the "rediscovery of the wheel" phenomenon. Most of the electrical breakdown and electrostatic discharge problems that will be faced in the Shuttle have been faced and solved in other hardware applications.

2.0 SUMMARY OF ELECTRICAL BREAKDOWN PROBLEMS AND  
ELECTROSTATIC VOLTAGE PROBLEMS

2.1 HIGH-VOLTAGE BREAKDOWN PROBLEMS

To identify some of the problem areas with high-voltage breakdown, a survey was undertaken by Stern and Mercy (ref. 1). This survey was an in-house effort at the National Aeronautics and Space Administration, Goddard Space Flight Center (NASA-GSPC). The survey included spacecraft administered by NASA during the period from 1961 to early 1968. Of particular interest to the survey was information on the following.

a. The nature of the breakdown phenomena; for example, gas ionization, including glow, corona, or arc discharges; and secondary emission, including multipactor discharges. (All these effects are described elsewhere in this manual.)

b. Systems affected by voltage breakdown

c. Known or suspected causes of breakdown phenomena

d. Conditions under which breakdowns occur

There were 74 problems analyzed. The results are summarized in figures 2-1 to 2-5. The voltages at which discharges occurred (fig. 2-3) ranged from 28 to 5000 volts. The breakdown at 28 volts occurred in 400-hertz regulators and pyro-power supplies on an Agena vehicle at separation from the booster. The environment which caused the breakdown is believed to have been caused by the plasma from the rocket plume. The majority of discharges occurred in a range of from 1000 to 3000 volts.

From figure 2-5, it is evident that design bears the largest burden of responsibility for voltage breakdown. Good design is one of those necessary, but not sufficient, conditions for success. After good design must come careful fabrication and testing. Accidental sharp points or edges on

high-voltage electrodes can cause electrical breakdown. Voids in the insulation or potting material can lead to the breakdown of the protective dielectrics and cause arcing. A fingerprint can prevent the potting material from bonding correctly and lead to arcing. Because of all the variables involved in producing a workable unit, the testing most desired is mission profile testing.

The effects discussed up to this point will be labeled as electrical breakdown. These occur with the application of alternating current (ac) and/or direct current (dc) potential. There is an ac and/or dc voltage supply and a circuit with ac and/or dc current flowing through it. There is another type of electrical discharge that occurs where nature supplies the high potential. This type, which will be labeled as electrostatic discharge, occurs when a high voltage is built up by the accumulation of charge. This accumulation of charge is usually, but not always, caused by frictional effects.

## 2.2 ELECTROSTATIC VOLTAGE PROBLEMS

A survey similar to the one above has not been made, to the author's knowledge, for the electrostatic discharge problem. The problem areas have, however, been identified by the workers in the field; for example, biological shock, fires, premature ignition of electroexplosive devices, mechanical effects, and radio interference. The systems affected have been man, the propulsion system, the ordnance system, the hydraulic system, and the complete range of avionics systems. In recent years, static electricity has also been found to interfere with computers, telemetry, tracking and guidance systems, sensors used to acquire scientific data, and thermal control systems.

Historically, system effects have been produced by the discharge of static electricity. In the last few years, it has been found that the mere presence of static electricity (in the absence of

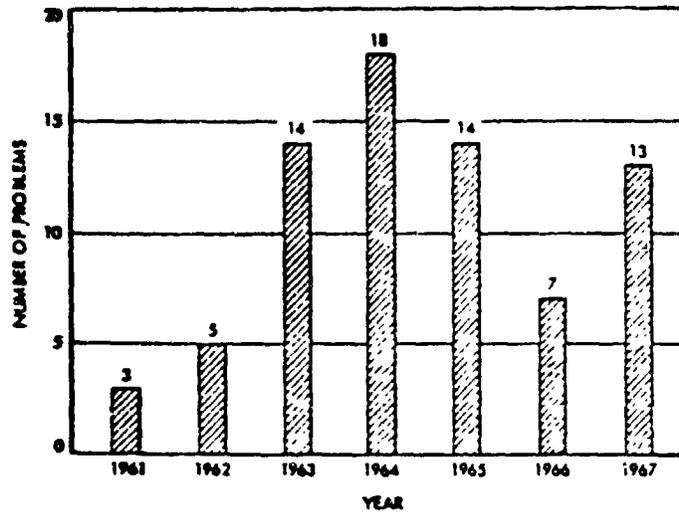


Figure 2-1.- Minimal annually reported voltage problems [from ref. 1].

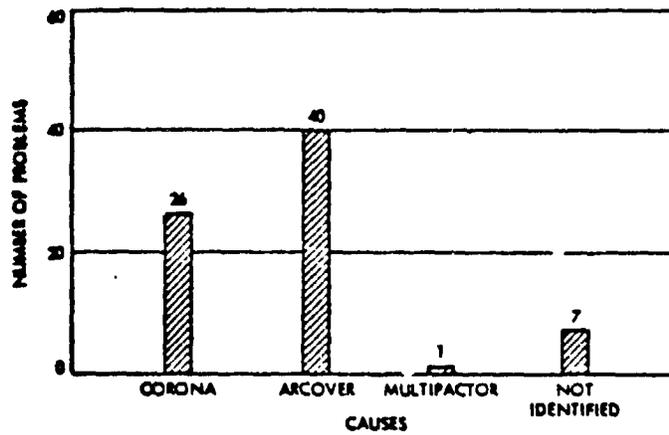


Figure 2-2.- Voltage discharge problems as identified [from ref. 1].

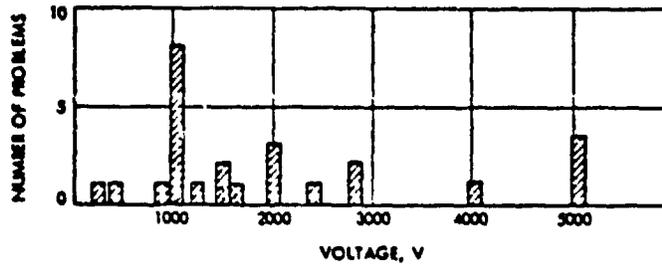


Figure 2-3.- Voltage levels at which breakdown occurred [from ref. 1].

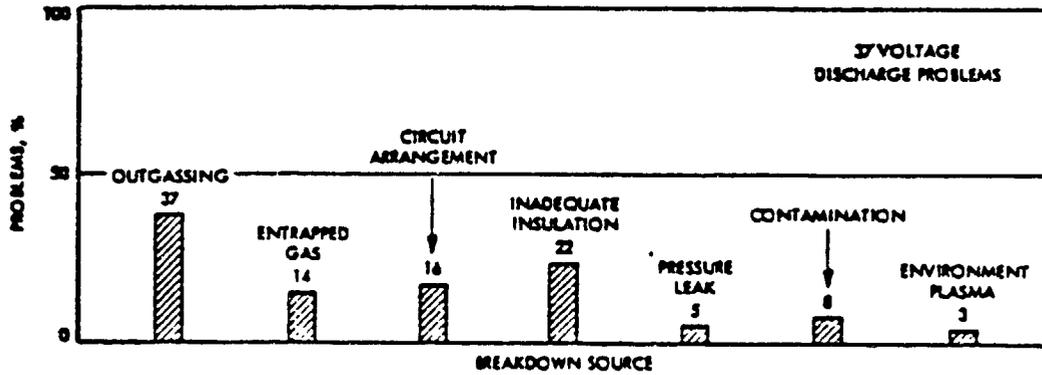


Figure 2-4.- Voltage discharge problem sources [from ref. 1].

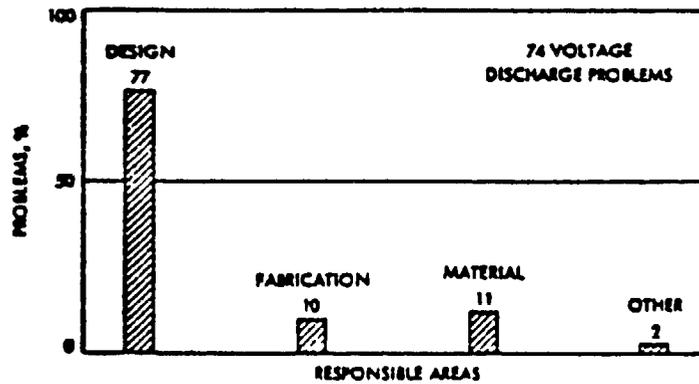


Figure 2-5.- Areas of responsibility for voltage discharge problems [from ref. 1].

discharges) can interfere with science instruments and thermal control systems, and can potentially affect contamination control systems as well.

### 3.0 PHENOMENA ASSOCIATED WITH ELECTRICAL BREAKDOWN

Electrical breakdown can occur in the gaseous, liquid, and solid states of materials. The effects are best understood and most easily described as they relate to gases. The object of this section is to give an intuitive understanding of electrical discharge.

#### 3.1 IONIZATION PHENOMENA

##### 3.1.1 Ionization of and Current Flow in a Gas

When a gas is not ionized, the individual molecules are electrically neutral. The negative charges of the orbital electrons are exactly balanced by the positive charge of the nuclei. Under these conditions, the gas acts as a perfect insulator; that is, no current will flow when it is subjected to an electric field. However, if free electrons are produced by an outside source (X-rays, beta-rays, ultraviolet light, cosmic rays, etc.) causing ionization of the gas molecules, a current can flow. If two electrodes with a potential difference between them are introduced into the gas, the free electrons will drift toward the positive electrode and the positive ions will drift toward the negative electrode. The drift velocity of these charged particles (electrons and ions) is slowed by random elastic collisions between the charged particles and the gas molecules. Each collision changes the electron's (or ion's) direction and velocity.

##### 3.1.2 Mean Free Path

The distance traveled between collisions will vary in a random manner; however, there will be an "average" or most probable distance for any given gas density. This distance is known as the "mean free path." The mean free path is inversely proportional to the density of the gas.

### 3.1.3 Space Charge

With a potential applied to the electrodes, the electrons are quickly carried away toward the positive electrode while the positive ions, which accelerate much more slowly because of their larger mass, are left behind. The resulting accumulation of ions is called a space charge. When both positive and negative gaseous ions are present, there can exist a space charge of either sign.

In the presence of a space charge, the electric field between the electrodes is the vector sum of the electric field from the applied voltage and the electric field from the space charge. The space charge tends to decrease current for a given applied voltage.

### 3.1.4 Condition for Electrical Breakdown

If the current carriers are being generated more rapidly than they are absorbed (by the electrodes or by recombination of electrons and ions), the gas will rapidly become a good conductor. At this point, electrical breakdown can occur. The production of current carriers happens through a number of different processes. Photoelectric ionization (ref. 2) is important at higher pressures (above 100 torr) but not of too much concern here. Secondary emission of electrons from the surface of the electrodes occurs when the impinging electrons have enough energy to kick an electron out of the metal. This effect is quite important when dealing with radio frequency (multipactor) breakdown. When the electron has enough kinetic energy to displace one or more electrons from the molecule with which it collides, the number of current carriers increases. The velocity (and therefore the kinetic energy) of the electron depends on the size of the electric field (not the voltage) and the distance traveled between collisions. The latter two processes will be discussed in greater detail later.

## 3.2

## ELECTRICAL BREAKDOWN AT SEA LEVEL

Electrical breakdown at sea level is shown in figure 3-1. As the voltage is increased from point A to B (starting at 0.0 volt), there is a linear increase (fig. 3-1 has a logarithmic current scale) in the current. This is called the Ohm's Law region and is a result of the free electrons available as a result of various ionization processes (cosmic rays, radioactive impurities, etc.). When all the free electrons are used up, the curve flattens out as from points B to C. This plateau is called the Townsend current or just free electron current. As the voltage is increased further, enough energy is imparted to the free electrons to enable them to strike some gas molecules and cause ionization, which results in a rapid rise of current as shown from points C to D. Depending on the conditions, this rapid rise of current can culminate in an arc

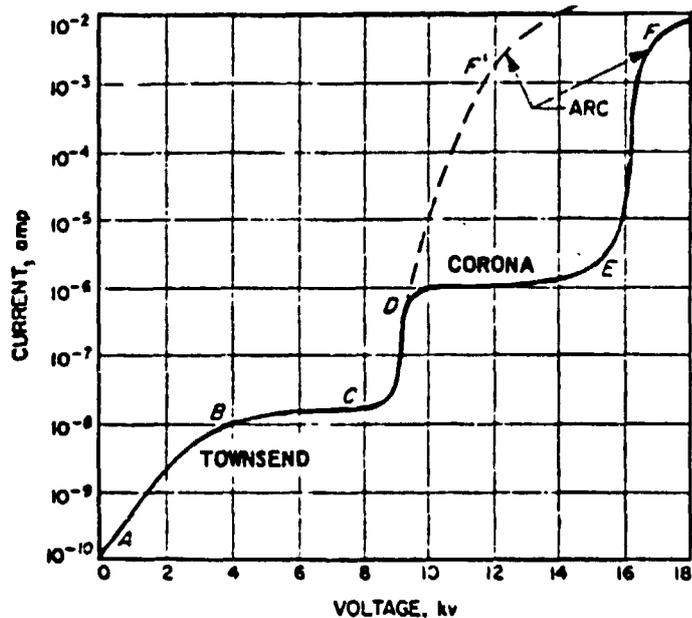


Figure 3-1.- Various types of voltage breakdown in air at sea-level pressure [from ref. 3].

shown as a dashed curve (D to F<sup>1</sup>) that is a complete breakdown between the electrodes, or the current may have a plateau which is called corona (this is a partial breakdown). As the voltage is increased further to point Z, the arc will form. When the pressure is reduced, equivalent to higher altitudes, it is increasingly difficult to distinguish between a corona and an arc.

Corona has been studied for about 90 years, but it is still difficult to obtain agreement on a definition. In contrast to an arc, corona is considered to be a partial breakdown. Bunker (ref. 3), has defined corona as 1.0 microampere of current. At sea level, the corona effect is a high impedance effect. With 500 volts and 1.0 microampere of current flowing, the equivalent impedance is 500 megohms, indeed a high impedance. Contrast this with a low-impedance arc where the current is only limited by the voltage and impedance of the power supply. As the number of molecules becomes less at lower pressures, the corona-to-arcing transition point, as shown by the step in the curve in figure 3-1, becomes less and less. In fact, an arc may occur with only 1.0 microampere of current. Thus, at low pressures, it is difficult to tell if the discharge is corona or arcing.

Of course, the power engineers have done considerable work on corona, because it represents a significant amount of loss in power transmission (besides interfering with radio and television). Most of their work has been done at 60 hertz and they consider that they are working at high altitude when they go up to 10,000 feet. Thus, much of what they have done is irrelevant to high-flight airplanes and rockets.

### 3.3 ELECTRICAL BREAKDOWN AT LOW PRESSURES

#### 3.3.1 Corona Onset Voltage

The parameter of most interest in low-pressure measurements is the corona onset voltage (COV). This is the voltage where self-sustaining corona

first starts. Also measured is the offset voltage or corona extinction voltage (CEV). This is the voltage at which corona is extinguished as the voltage is lowered after corona has been obtained. The CEV can be significantly lower than the COV.

3.3.1.1 Detection of corona onset voltage.- At times, it is difficult to determine experimentally what the COV value actually is. At sea level, the main manifestations of corona are a blue haze, a crackling sound, the smell of ozone, and some radio frequency (rf) noise. As the pressure is lowered, the acoustical noise and production of ozone are not very useful for the detection of corona. Also dc corona can be produced with no rf noise (ref. 3). If the electrodes are placed inside an opaque box, the visible light cannot be used as an indicator of COV.

Perhaps it is best to stick to definitions of corona such as that given by Loeb (ref. 4): "The general class of luminous phenomena, associated with a current jump to some microamperes, appearing at the highly stressed electrode, and preceding the ultimate spark breakdown of the gap" or by Dunbar (ref. 5): "Corona is a luminous discharge (first observed as a point on a negative electrode and as a thin film over high field areas of a positive electrode) caused by ionization of the air (or other gases) surrounding a conductor around which exists a voltage gradient exceeding a critical value. This critical gradient is one which will cause electrons to separate from gas molecules leaving behind charged atoms or ions. This energy absorption by gas in this ionization process is measurable as current. The reionization process in which the electrons and ions recombine releases this absorbed energy as light which is the visual corona. Corona can also be considered as a partial discharge through the gas between two open or partially encapsulated electrodes, measurable as a momentary current flow in the order of  $10^{-8}$  to  $10^{-6}$  ampere peak."

In the systems of interest, corona is almost always a pulse phenomenon, which distinguishes it from continuous electrical discharges such as arcing. This pulse is generally less than 0.1

microsecond with a repetition rate that may be low. Corona also occurs as a continuous series of pulses with frequencies up to about 200 kilohertz. This corona frequency (pulse repetition rate) is a function of corona current and absolute pressure (ref. 5). These short-duration pulses can radiate high-frequency components well into the 100-megahertz region. This radiation can be detected and used as an indication of corona discharge. Of course, one of the reasons that corona should be eliminated or minimized is that this radiation can be a major source of interference for sensitive instruments and communication equipment.

The "Corona Test Procedure" for the Space Shuttle (section 4.2.5.2 of ref. 7) is provided as follows. (Refs. 8 to 12 contain more information on the detection of corona.)

"Corona Test Procedure. The high voltage lead from the power supply shall be connected to one insulated conductor. The case and all other common connections, which are isolated (open circuited) from the insulated conductor connected to the power supply, shall be connected together. A lead from the common connections shall be taken to the vertical input of the oscilloscope. The RF choke shall be connected across the oscilloscope input terminals. A lead wire shall be connected from the ground oscilloscope terminal to the ground connection of the power supply. Test procedure steps shall be as follows:

"a. Adjust the sweep rate on the oscilloscope to display several cycles of the ac voltage and observe the wave form. Apply a low voltage to the test terminal, then increase the voltage to 150 percent of the specified rated voltage. If corona is present, the corona will appear as spikes near the peaks of the ac waveform. Precautions should be taken to ensure that corona is occurring in the equipment under test, not in the test leads, terminals, or associated apparatus. Any point of breakdown, after three or four repeatable cycles, will be quite sharp and stabilized. The breakdown voltage should be observed only after stabilization. Any indications of corona, as

exhibited by spikes or other irregularities appearing on the oscilloscope when tested up to 150 percent of the specified rated voltage (rms) shall constitute failure of this test.

"b. When increasing the test voltage, the lowest voltage at which the spikes appear is the CIV (corona initiating voltage); when decreasing the test voltage, the voltage at which the spikes disappear is the CEV (corona extinction voltage). Both the CIV and CEV values shall be recorded.

"c. Equipment having more than one voltage applied to different circuits or connections will require testing of each circuit at each specified voltage. Any terminal or connection rated at less than 50 volts ac or dc need not be tested.

"d. When testing relays or switches, repeat the test with the part actuated."

#### 3.3.1.2 Physical reason for pulses in corona breakdown.

Free electrons released in the gas near the positive electrode move toward it. If there is a strong electric field, the electrons gain energy rapidly and they produce many ions in a small volume near the anode. When sufficient ions exist, a positive streamer moves outward from the anode. The electrons are gathered by the positive electrode (anode) and the field is weakened as the positive space charge builds up. This gives rise to a tendency for the positive corona to choke itself off. If it does choke itself off at this point, it, of course, has produced a pulse. At this particular voltage, pulses of corona would then occur.

As the applied potential is increased, causing higher electric fields, the streamers propagate further toward the cathode. At this point, in place of the occasional short streamer and the flickering bright blue film (ionized air) at the anode, longer streamers project outwards. These streamers have a characteristic brushlike appearance. In air, they are bright blue in color. The ions left behind, which produce the space charge, show general purple haze characteristic of a low-voltage discharge in air.

The brush discharge is a positive corona with a purple haze pierced by large numbers of bright blue streamers. As the potential is increased still more, the streamers will propagate to the nearest cathode. When they reach the cathode with enough intensity, a spark results, followed by a glow, arc, or extinction depending on the discharge conditions. If the discharge conditions are such that the current flow is extinguished, the whole process will shortly repeat itself, thus forming a series of pulses.

3.3.1.3 Electric field stress points.- The shape of the electrodes can have a pronounced effect on the COV. At sea-level pressures, it is of paramount importance; but, at lower pressures, especially near the Paschen minimum (section 3.3.2.6), the geometry of the electrodes becomes less important.

Three things determine the electric field at any point in space: (1) the applied potential, (2) the geometry of the electrodes, and (3) the space charge. The effect of the electrode shape is illustrated in figure 3-2. In this figure, it is assumed that the electrode is in free space (vacuum, no space charge) and that the second electrode is far enough away not to distort the field lines close to this electrode.

Note that the field lines are concentrated around the point. This means that any discharge will most likely come from this point. It also means that the discharge will occur from the sharp point at a lower applied potential than it would from the blunt point. The radius of curvature is the important parameter in this respect. The smaller the radius of curvature, the more concentrated the electric field lines are. Needle points (essentially zero radius of curvature) and parallel-plates (essentially infinite radius of curvature) provide two extremes in electric-field line concentration. Parallel plates have parallel well-defined uniform fields, whereas needle points have extremely nonuniform fields. The corona characteristics of electrical components vary between these two extremes.

Screw threads, nut tips, very thin wires, and poor solder joints are examples of points. Relay contacts, buses, and variable capacitor plates are examples of parallel plates.

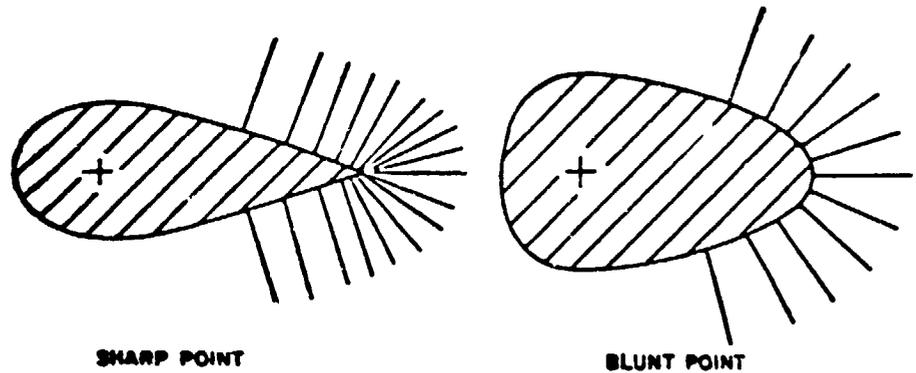


Figure 3-2.- Electric field lines for two different geometries in free space.

Plotting or calculating the electric field gradient near a high-voltage electrode is probably the most effective method for determining the electrical stress pattern near nonplanar electrodes. References 10 and 12 contain some of these plots along with some equations for calculating the field values. However, field plotting and field analysis are tedious work and it is often more expedient to estimate the maximum field gradient near a nonplanar electrode. Some of these maximum gradients, as a multiple of the average field gradient, are shown in table 3-I.

TABLE 3-I.- FIELD GRADIENTS

[From ref. 13]

Configuration	Field gradient (per unit V/mm)	
	Average	Maximum
Parallel plates	1.0	1.0
Coaxial	1.0	2.7
Small wires, points, round rod edges	1.0	5.8

Other estimates of the electric field near a point electrode are even more severe than those in table 3-I. For example, Paul and Burrowbridge (ref. 2) consider a rounded electrode with a 1-centimeter radius of curvature with applied voltage such that the electric field near the electrode is 200 V/cm. If the position of the electrodes is not changed and the radius of curvature is reduced to 1 millimeter, the electric field becomes 20,000 V/cm. If the radius is reduced to 0.1 millimeter, the field strength near the electrode is 2,000,000 V/cm. This tremendous increase in electric field occurs without any change in position or applied voltage.

Edges of electrodes can also produce very high localized fields if they are sharp or have small radii of curvature. These very high fields can lead to electrical breakdown by accelerating electrons and ions and by producing field emission of electrons that contribute further to electrical breakdown. Field emission can pull electrons from a solid surface, even when it is cold, clean, and not irradiated, if the electric field at the surface is greater than  $5 \times 10^5$  V/cm. This huge field can occur, as mentioned before, with very moderate applied voltages if sharp points or edges exist. It is also possible for very high field strengths to exist as two parts of a mechanical switch approach each other in the process of

closing. Thus, breakdown can occur by field emission upon closing as well as by the familiar spark that occurs when the circuit is broken.

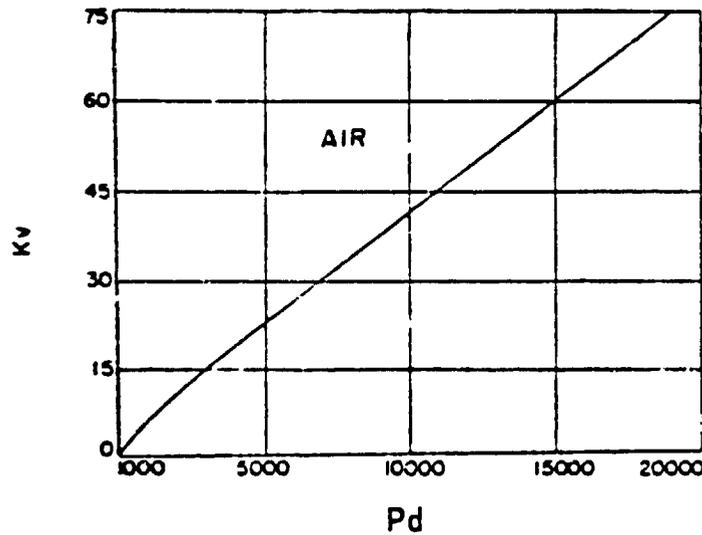
The character of the surface of the electrodes is also important. Local surface irregularities such as pits and blowholes can produce local field concentrations that lead to electrical breakdown. The surface finish should be as smooth as possible.

It is possible to have nonuniform fields even when the electrodes would indicate a uniform field (e.g., two large smooth parallel plates). This can occur with the presence of space charge. The generation of nonuniform fields in this way requires unequal concentrations of positive and negative charge. This is not uncommon in gas discharges.

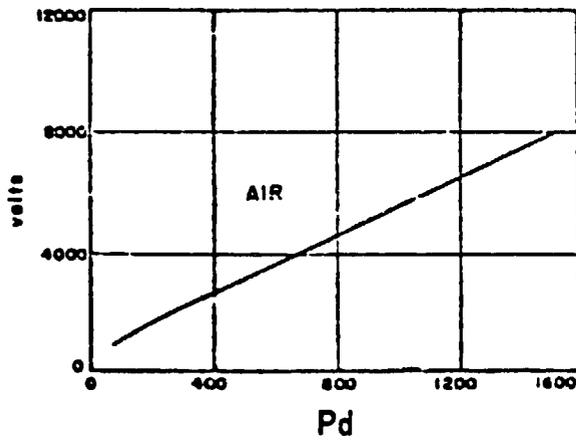
Because the velocity of the electrons depends on the electric field (and on the mean free path), ionization and corona discharge could occur even when the size of the applied voltage would not indicate the possibility of it. Thus, the effects of electrode shape and space charge must be considered in the design stage.

### 3.3.2 Paschen's Law

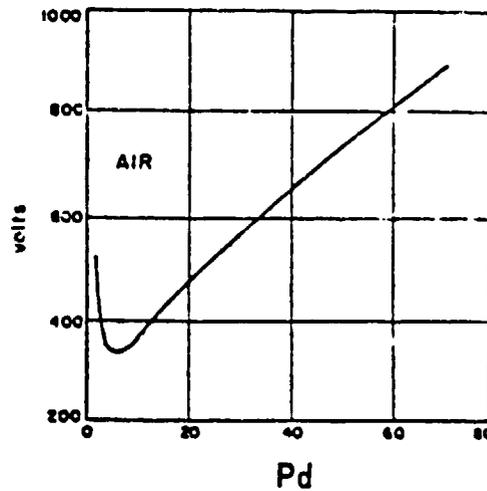
3.3.2.1 COV vs. pressure and Paschen's minimum. - The single most important graph for work with corona is the one illustrating Paschen's minimum. Paschen's law was discovered experimentally in 1889 and verified theoretically (ref. 14) 20 years later by Townsend. The three curves of figure 3-3 show the behavior of the breakdown voltage as a function of the pressure  $P$  times the separation  $d$  between two parallel plates. For any given  $Pd$  product, there is a breakdown potential where an arc occurs (Paschen's Law). For example, air at room pressure breaks down at about 75 kilovolts which is a  $Pd$  product of about 19,000 (mm Hg) X (mm). Then, as the separation and/or the pressure decreases, the curve is approximately linear. The curve remains linear until low values of  $Pd$  are reached. The Paschen minimum is illustrated in



(a) Arcing-voltage range from 0 to 75 kv.



(b) Arcing voltage range from 0 to 12000 V.



(c) Arcing-voltage range from 200 to 1000 V.

Figure 3-3.- Arcing voltage vs. Pd, product of pressure and separation of parallel plates. (Pd is in mm Hg times mm of separation.)

figure 3-3(c). After passing through the minimum, the breakdown voltage increases with decreasing  $Pd$ .

3.3.2.2 Conditions for Paschen's Law.- This type of curve is used to analyze many different types of electrodes and situations. Strictly speaking, however, there are only three conditions under which Paschen's Law holds (ref. 3), as follows.

1. There must be a uniform field.
2. Spacing of the two plates is large compared with the mean free path of the gas molecules.
3. There are no space charge effects in the gap.

If these three conditions are met, the repetition of the experiment for gaps of various lengths will yield curves that fall on top of one another (Paschen's Law). However, condition 1 can only be met by parallel infinite planes. A good approximation is, of course, obtained when both the width and breadth of the plates are a good deal larger than the distance between plates. Condition 3 is no longer met at low pressures and condition 2 does not hold at and below the minimum.

3.3.2.3 Physical reason for Paschen's minimum.- The reason for the Paschen minimum is that, as the density of the gas decreases, the mean free path of the electron increases. Because the velocity acquired by an electron depends on the intensity of the electric field and the distance traveled between collisions, a decrease in pressure means an increase in the average kinetic energy of the electrons. As the energy of the electrons increases, they produce more ionization. If current carriers are being generated more rapidly than they are being absorbed, the gas will become a good conductor and corona or arc-over will occur. Thus, for a given pair of electrodes, the potential difference necessary to initiate a discharge decreases as the pressure (and therefore the density) of the gas is reduced. This effect

continues until the mean free path becomes comparable with the electrode spacing. At this point, the probability of a collision between each electron and a gas molecule decreases, and the breakdown voltage increases quite rapidly as the pressure is lowered further.

In all the preceding, it has been assumed that the temperature is constant. The mean free path is really a function of density and, for a given pressure, the density would change with temperature.

3.3.2.4 Experimental determination of Paschen's minimum.-  
The minimum breakdown voltage for air with parallel plate electrodes is about 330 volts and occurs at  $Pd = 5$  torr X mm (1 torr = 1 mm Hg). The shape of the electrodes, the type of gas, and the relative humidity all affect the Paschen-type curves, as illustrated in figures 3-4 to 3-6. Even the type of material the electrode is made of can influence the curve; for example, in an argon atmosphere, aluminum electrodes have a lower Paschen minimum than steel electrodes (ref. 12).

The only way of being sure of the Paschen minimum for any given configuration is to take the data points and plot the curve. In doing this, care must be taken to avoid some experimental pitfalls. Mercury contamination can be a real problem, unless it is very carefully trapped out, when a mercury manometer or a McLeod gage is used. The presence of mercury vapor will cause breakdown at a much lower voltage than otherwise. As the frequency increases, the electrical breakdown occurs at a lower voltage (section 3.3.5). The waveform of the applied voltage will influence the COV. The type of insulation on the electrodes will have an effect. Outgassing of organic materials can change the atmosphere and the pressure. Creepage paths (section 3.4.4.3) can cause breakdown after the apparatus has performed well for a time. Cleanliness of the electrodes is important. If the electrodes are touched, the oil from the fingers will increase the breakdown possibilities in that area. Almost clean-room facilities are required. At least one free electron must be in the gap before corona or an

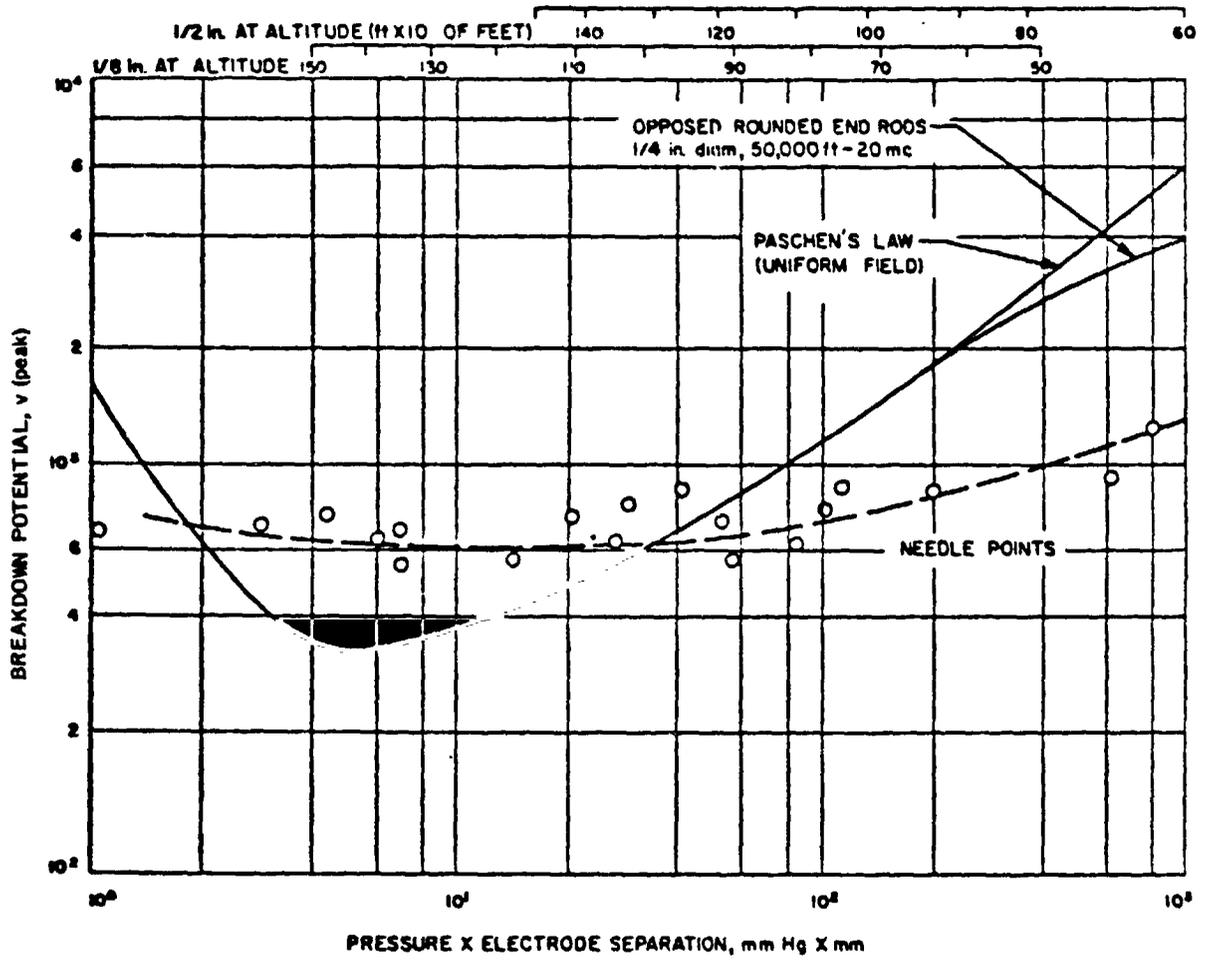


Figure 3-4.- Comparison of uniform field breakdown through critical pressure range [from ref. 15].

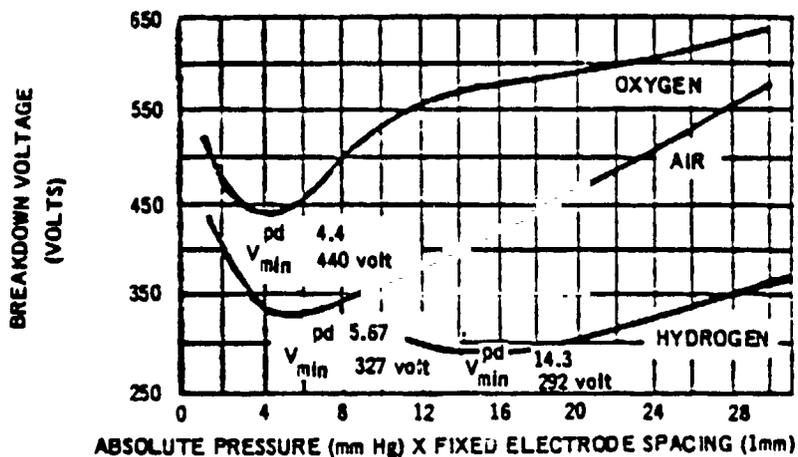


Figure 3-5.- Paschen's Law curves for oxygen, air, and hydrogen with electrode spacing fixed at 1 millimeter [from ref. 6].

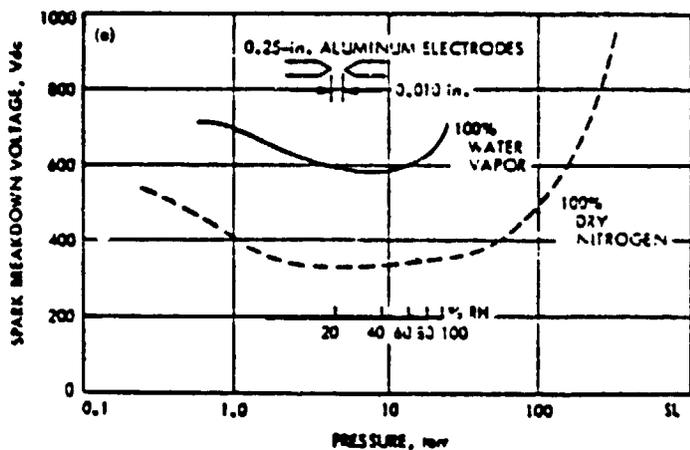


Figure 3-6.- Spark breakdown threshold as a function of the pressure and gas environment [from ref. 16].

arc will form. Cosmic rays do supply ionization, but on a random basis. To make the breakdown more easily measurable, a source of electrons, such as a radioactive source or an ultraviolet source, is usually provided for the experiment.

- 3.3.2.5 Critical region.- The critical region is the pressure range where corona is most likely to occur. This range, of course, encompasses the Paschen minimum. The critical air pressure region has been arbitrarily defined as the range of air pressures at which the dielectric strength of the gas is 20 percent or less of the value at sea level. This range is about 60,000 to 310,000 feet in altitude or, equivalently, 50 to  $5 \times 10^{-4}$  torr in pressure.

For each electrode spacing, there is, of course, a unique pressure at which minimum COV occurs. This means that each electrode spacing has its own critical region. The electrical system of an aircraft or space vehicle has many components with a variety of spacings between conductors, contacts, and terminations. Thus, the critical region for the entire system would be much larger than it would be if only one set of electrodes were considered.

- 3.3.2.6 Experimental effects of Paschen's minimum.- For pressures above the Paschen minimum, an increase in spacing between the electrodes will raise the COV (assuming the pressure to be held constant). However, for pressures below the minimum, increasing the spacing will decrease the COV; that is, at these pressures, the COV decreases with increasing Pd.

This property has some interesting effects. For example, below the Paschen minimum, the discharge will not originate at the point of minimum spacing but will start where the spacing is most favorable and will usually spread over a wide region. At gas pressures above the minimum, the discharge will usually be confined to a region of maximum potential gradient (electric field). This may be at the point of minimum spacing or at a sharp point on a conductor. At the higher pressures, the elimination of sharp points (small radius of

curvature) on conductors will considerably increase the breakdown voltage; but at pressures in the neighborhood of and below the Paschen curve minimum, there is relatively little effect.

Because of the Paschen minimum, the size of the vacuum chamber can have an effect on the discharge. At pressures approaching high vacuum, the discharges will follow the longest path possible in a chamber, actually avoiding nearby conductors of the opposite polarity. Thus, the pressure and voltage at which gas discharges can still occur will be lower in larger and extended chambers than in smaller chambers.

### 3.3.3 Glow Discharge

In contrast to most discharges at higher pressure, breakdown between conductors in the pressure region in the vicinity of Paschen's minimum usually has the characteristic of a glow discharge. Glow discharges have a greater internal resistance together with a tendency to spread over a substantial volume of the chamber. Also in contrast to electrical breakdown at higher pressures, the glow discharges do not instantly tend to develop into an arc between conductors with a low voltage drop. They require higher current levels to form an arc and these current levels may not be available from the circuit under consideration. In this case, glow currents of many milliamperes may flow and substantial voltages be maintained, without forming an arc.

### 3.3.4 The Law of Similitude

The Law of Similitude, or the Similarity Principle, states that the volt-ampere characteristic of a given gas discharge system will not change if all the linear dimensions of the system are increased by a constant factor  $K$  and the gas pressure is reduced by the same factor, or vice versa. This principle is illustrated in figure 3-7. Through using techniques such as dimensional analysis, this

principle can be quite useful in dealing with complex geometries or nonuniform fields.

If the Law of Similitude is applied to the case of breakdown along a uniform field path, it becomes a statement of Paschen's Law. For the Law of Similitude to be obeyed, all processes which determine discharge behavior must be functions of  $E/P$  only.

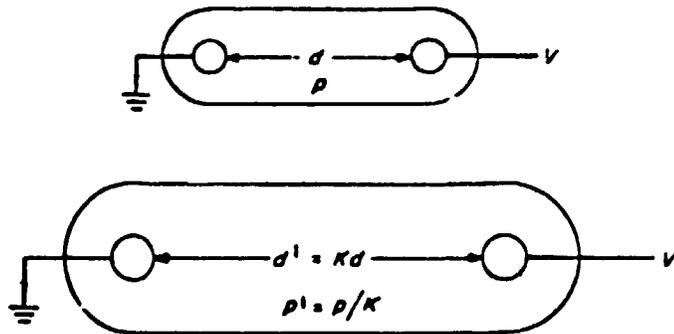


Figure 3-7.- Law of Similitude.

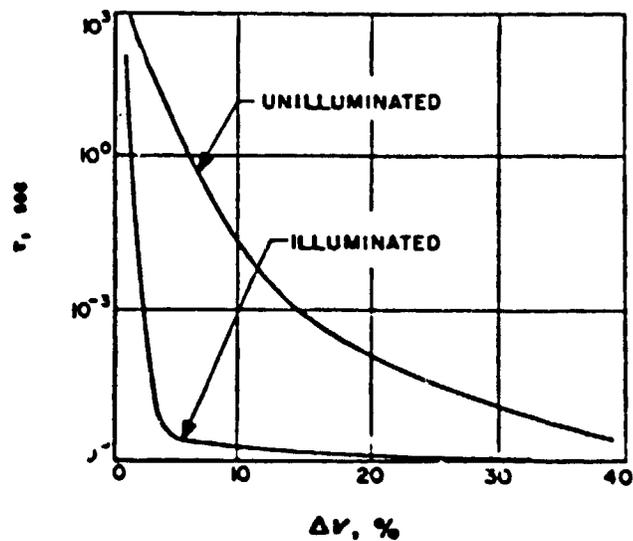


Figure 3-8.- Breakdown time  $\tau$  vs. overvoltage  $\Delta V$  for illuminated and unilluminated gaps [from ref. 3].

### 3.3.5 Effects of Wave Shape and ac on Electrical Breakdown

For discharge to occur, there has to be at least one electron in the gap. The free electrons in the gap are produced by nature through cosmic rays and radioactive impurities. Because these sources are random, the discharge does not always start immediately with the application of the COV. Figure 3-8 shows the average breakdown time  $\tau$  for a given voltage,  $V = \text{COV} (1 + \Delta V)$ ; that is,  $\Delta V$  is given in terms of percent voltage above COV. When the gap is illuminated by a radioactive or ultraviolet source, the time  $\tau$  is reduced dramatically.

For dc voltages, the time  $\tau$  has no real significance, but for pulses and ac it can be significant. A pulse with the amplitude  $V_s + \Delta V$  ( $V_s$  is the threshold voltage or COV) and a pulse length much longer than  $\tau_1$  (breakdown time for overvoltage  $\Delta V_1$ ) will break down practically every time (fig. 3-9). As the pulse length is shortened until it is of the order of  $\tau_1$  (point A), then there will only be intermittent breakdown. If the pulse length is much shorter than  $\tau_1$ , then the probability is good that there will be no breakdown even with a large  $\Delta V_1$ . Of course, if the amplitude is increased to  $\Delta V_2$  with a pulse length of  $\tau_1$ , breakdown will again occur regularly. Decreasing the width of the pulse (with  $\Delta V_2$  overvoltage) to  $\tau_2$  will again produce intermittent or no breakdown.

For an arbitrary wave shape (fig. 3-9(b)), the voltage can build up to the maximum and be decreasing before breakdown occurs. When it breaks down depends on the length of time and the overvoltage applied.

For an ac voltage (or series of pulses close together), the effect is cumulative; that is, if the peaks are closer together than the lifetime

of the charges produced by the overvoltage, then the effect of the peaks add together.

If the peaks (or pulses) are far enough apart, there is enough time for the electrons to disappear and conditions would be as in figure 3-9. Figure 3-10 shows a typical sine wave going above the threshold for a period of time  $t$  on each cycle. Electrical breakdown becomes likely when  $nt = \tau$ , where  $n$  = number of cycles and  $\tau$  is found from figure 3-8, where  $\Delta V = V_p - V_s$  is a good approximation ( $V_p$  = peak of sine wave) for finding  $\tau$ . It may take several cycles for the breakdown to occur.

Implicit in the discussion is the effect of frequency on breakdown voltage. Figure 3-11 shows this dependence explicitly.

### 3.3.6 Multipaction or rf Breakdown

At frequencies greater than  $10^6$  hertz, a new phenomenon begins to be important in breakdown behavior. This phenomenon, called multipaction, is associated with charged particle resonance. The effect of multipacting on the Paschen curve at low pressures is illustrated in figure 3-12. The pressure is in micrometers of mercury. Most of the communications between spacecraft and ground stations takes place at frequencies in the 20- to 2000-megahertz range. The design and fabrication practices for this frequency range are somewhat different than those for dc. These differences are due mainly to multipaction.

The effect does not occur until the mean free path is larger than the gap; that is, below the Paschen minimum. The multipactor discharge is basically a resonance phenomenon, as shown in figure 3-13. The electric field of the rf oscillations accelerates the electrons in the gap. When the electron strikes the electrode, it can produce secondary emission. If the frequency and phase are just right, the secondary electrons will be accelerated toward the other electrode

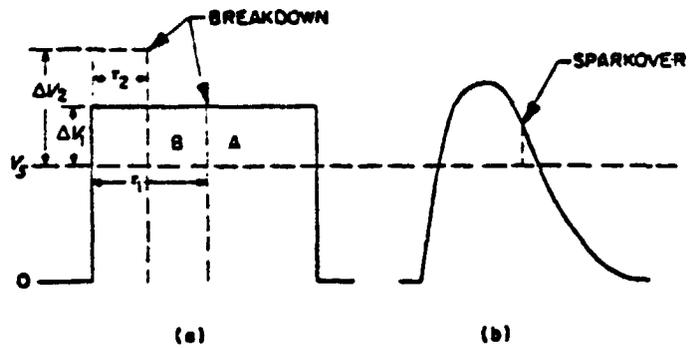


Figure 3-9.- Waveform effects on time for voltage breakdown, square wave and pulse [from ref. 3].

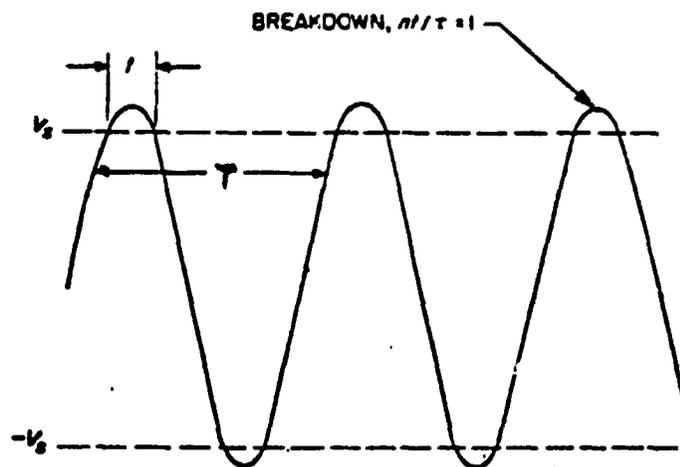


Figure 3-10.- Waveform effect, ac voltage breakdown [from ref. 3].

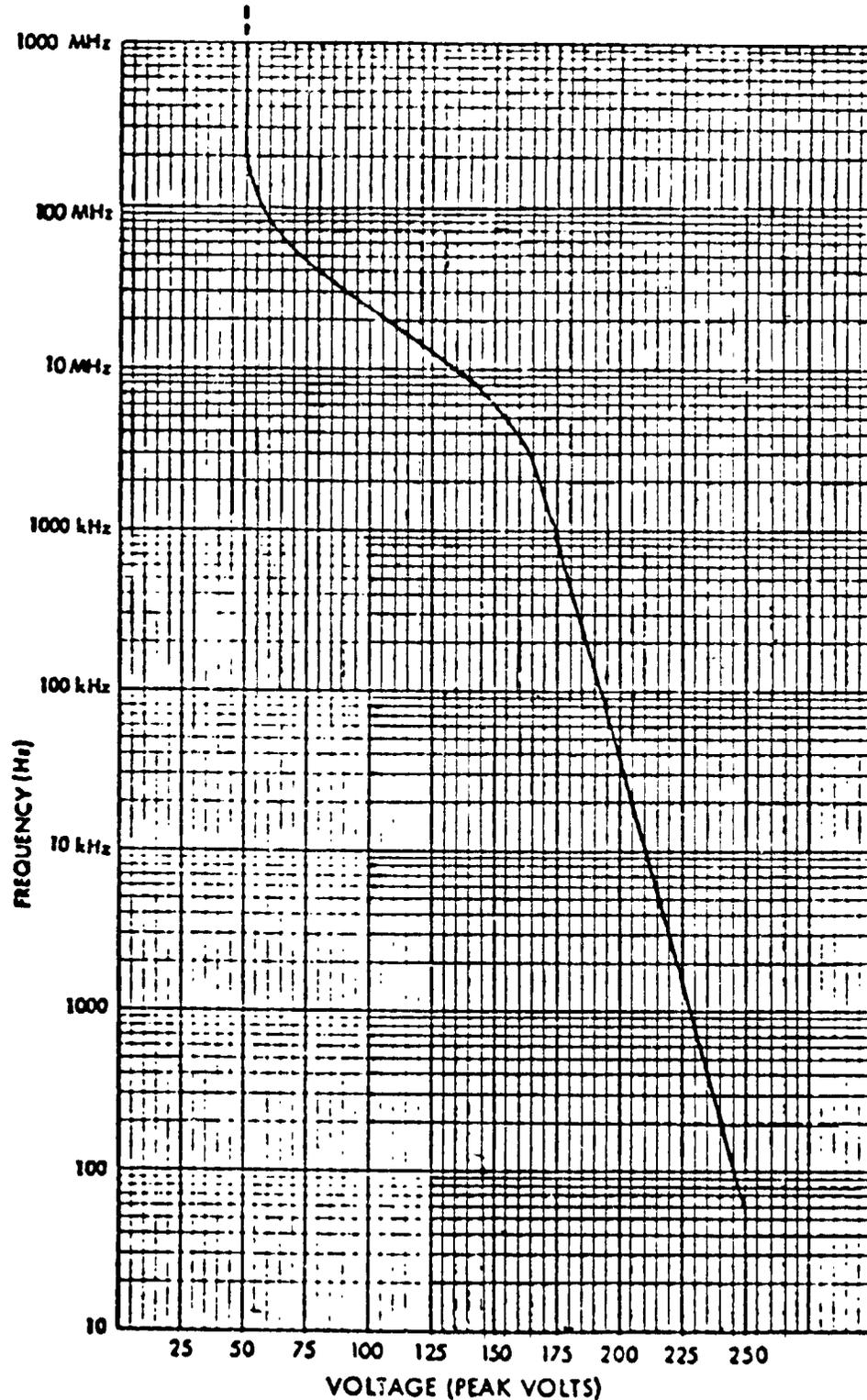


Figure 3-11.- Lower voltage breakdown limit vs. frequency for Earth atmosphere [from ref. 11].

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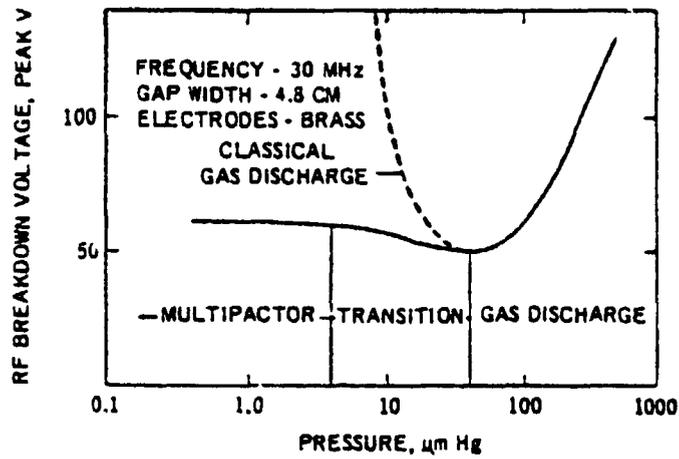
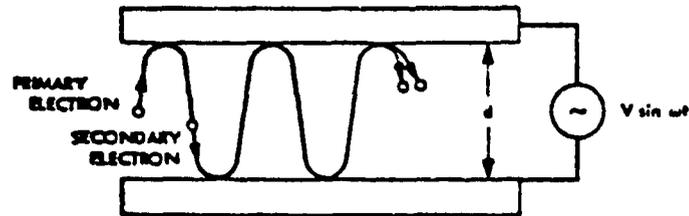


Figure 3-12.- Paschen's curve as modified by multipacting [from ref. 17].



APPROXIMATE OPERATING CONDITION:

$$d = 2 \times \text{EXCURSION} = 2 \frac{eE}{m\omega^2}$$

$$V = Ed = 2e^2 \frac{m}{\omega^2} (f_d)^2$$

Figure 3-13.- Multipactor discharge: electron resonance in an rf field, with discharge sustained by secondary emission [from ref. 17].

and the process will repeat itself. Multipaction is thus a resonance effect. The upper formula in figure 3-13 gives the relationship between gap size  $d$ , amplitude of the electric field  $E$ , and frequency ( $\omega = 2\pi f$ ). The breakdown voltage  $V$  is also given. This voltage is overestimated by the factor  $\pi$  because of the simple theory used (ref. 17).

The transmitting system is affected in many different ways by multipaction. There is some rf power lost in exciting the electrons. When sufficient gas molecules are present, ionization can occur, which can cause corona with the resultant breakdown between plates. The impact of the electrons on the surface can cause heating and outgassing. The load on the rf source is reactive, which causes detuning of the output circuits. An increase in the harmonic output from the transmitter is caused by this nonlinear load. Also, noise is generated by multipactor effects, which can interfere with nearby receiving equipment. All these effects will probably not happen together. The antenna may be perfectly useful as a radiator after breakdown, but its efficiency with respect to total radiated power will be drastically reduced.

Someone not familiar with multipactor effects could interpret these symptoms as indicative of some other cause. This may be the explanation of a loss of the S-band subcarriers (ref. 18) in Apollo 7. The report states, as follows.

"The failure was characterized by:

"a. Drop in the ground-received PM signal strength

"b. Loss of PM subcarriers

"c. Lower than expected transponder-received signal strength.

"No other abnormalities were detected. The only components within the S-band system which could have failed and caused all these symptoms are the panel switch for selecting the primary or

secondary transponder and the wiring which controls this function. The switch was X-rayed and functionally tested postflight with no abnormalities noted. The transponder was tested in the command module and on the bench, including vibration and temperature acceptance testing, and the results were all negative.

"When the select switch is changed from one transponder to the other, a momentary hesitation in the OFF position is required to allow latching relays to reset. Switching without this hesitation can cause both transponders to be ON and will create all the symptoms of the failure.

"The transponder select switch, directly above the antenna select switch, may have been inadvertently thrown during one of the frequent antenna switchings, and both transponders may have been activated. Although the crewmember on duty cannot remember inadvertently throwing the wrong switch, he does not discount the possibility.

"No further actions is required, and this anomaly is closed."

Symptoms (a) and (c) could easily have been due to multipacting. Symptom (b) would have to be checked out. The thing to note is that multipaction was not even considered as a possible failure mode. Also, the suspected elements showed no abnormalities even when X-rayed. The transponder was checked but apparently at sea-level pressure where multipacting would not occur. This possible misinterpretation of an anomaly just points out the need for greater assimilation of knowledge about electrical discharge.

Electrode spacing, frequency, and the applied voltage must all be considered when considering design parameters for the elimination of multipacting. Figure 3-14 displays one set of relationships among these parameters. The peak voltage is the ordinate while the product of frequency and electrode separation is the abscissa. The scale at the top is electrode separation divided by wavelength, both in the same units. The three regions indicated by  $1/2$ ,  $3/2$ ,

and  $5/2$  are where multipacting can occur. The electrons that correspond to the region marked  $1/2$  have a transit time of  $T/2$ , where  $T = 1/f$ . Those in region  $3/2$  have a transit time of  $3T/2$ , et cetera. Unfortunately, a general plot of this sort cannot be relied on for design data, because the values depend on factors such as number of electrodes, electrode material, surface conditioning of electrodes, and geometry (e.g., parallel plate, coaxial, etc.). The designer is forced to test each design at various stages of fabrication to be certain that multipacting is not occurring.

Some design features that have been known to help (ref. 2) are as follows.

1. The insertion of foamed dielectric material between the electrodes
2. Treatment of electrode surfaces to change their secondary emission characteristics
3. The application of dc bias to the electrodes to suppress secondary electron emission
4. Pressurization of the space between the electrodes
5. The selection of electrical and mechanical dimensions to reduce the likelihood of multipaction

Before anything can be done to prevent multipaction, it, of course, has to be detected. There are three prevalent methods of doing this. One is the observation of the faint glow that results from ionization of the gas. However encapsulation (section 3.4.3.3) would eliminate the use of this method. Phosphorescent materials placed near the multipactor area will glow under bombardment of the electrons. However, this could affect the conditions existing in the area. The most sensitive and satisfactory detector consists of a collector electrode in the suspected area. A dc current will flow to the electrode if a small dc voltage is applied and a discharge is present.

### 3.3.7 The Malter Effect or Clumping

The "clumping" mechanism occurs when the electric field is large enough to remove a charged particle of material from one electrode and then accelerate it to the opposite electrode. The impact releases enough energy to produce localized heating which creates a vapor cloud. This is usually followed by voltage breakdown. This type of field emission is caused by an impure cathode. The surface charges can be caused by photons from a preceding discharge or from an outside source. One effect is to lower the COV for values of  $F_d$  below the Paschen minimum.

### 3.4 ELECTRICAL BREAKDOWN IN SOLID INSULATORS

The electrical breakdown characteristics of solid insulators are particularly important in the design and fabrication of spacecraft systems because solids are widely used to prevent undesired electrical discharges. Examples of such applications are insulating sleeves on wires, solid potting compounds, and conformal coatings.

Insulators by their very nature are dielectrics; that is, when an electric field is applied to an insulator, the atoms (or molecules) will polarize rather than give up an electron for conduction. The size of the dielectric constant has some important effects in the electrical breakdown modes of the solid dielectric (section 3.4.4).

### 3.4.1 The Gas-Solid Interface

#### 3.4.1.1 Voltage distribution between the gas and the solid.-

The breakdown voltage of solids is many times higher than that of gases. The start of cumulative ionization is the beginning of dielectric breakdown in solids as it is in gases. Solid insulators generally have much greater dielectric strength than gaseous insulators. Thus, in a gas-dielectric interface, the initial electrical breakdown will almost invariably occur in the gas. The COV for the gas can be determined by using established curves for various gap distances and electrode configurations. To determine the COV for the gas-dielectric system, all that is left to determine is the fraction of the total voltage that is dropped across the air gap.

A good model of the gas-dielectric system is a dielectric-filled capacitor in series with a gas-filled capacitor. This system is shown in figure 3-15.

Dunbar (ref. 10) shows that

$$V_2 = \frac{V}{\left(\frac{t_1 \epsilon_2}{t_2 \epsilon_1}\right) + 1} \quad (3-1)$$

where  $t_1$  = thickness of the solid dielectric

$t_2$  = thickness of the gas dielectric

$\epsilon_1$  = dielectric constant of the solid

$\epsilon_2$  = dielectric constant of the gas

$V_2$  = voltage drop across the gas

$V$  = total voltage drop of the system

Of course,  $V = V_1 + V_2$ , where  $V_1$  is the voltage drop across the solid (fig. 3-15).

For all practical purposes, the COV of the system can be found by substituting the COV of the gas for  $V_2$ ; that is,

$$(\text{COV})_{\text{system}} = (\text{COV})_{\text{gas}} \left( 1 + \frac{t_1}{t_2 \epsilon_1} \right) \quad (3-2)$$

where it has been assumed that  $\epsilon_2 = 1.0$ , which is a good approximation for most gases. The COV of the gas can be found by using the experimentally determined Paschen-like graph. The value of electrode separation that should be used is, of course,  $t_2$ . The COV of the system can then be found if  $\epsilon_1$  and  $t_1$  are known.

Another model that has been found to be useful is shown in figure 3-16. This model could qualitatively represent two insulated wires close together, an insulated wire near an insulated plane surface, or many other configurations. The COV of the system can be estimated by using the equation<sup>1</sup>

$$(\text{COV})_{\text{system}} = (\text{COV})_{\text{gas}} \left( \frac{t_1}{t_2 \epsilon_1} + 1 + \frac{t_3}{t_2 \epsilon_3} \right) \quad (3-3)$$

where  $\epsilon_2 = 1.0$

$t_3$  = thickness of second solid dielectric

$\epsilon_3$  = dielectric constant of second solid dielectric

$V_3$  = voltage drop across the second solid dielectric

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<sup>1</sup>Equation 13 in reference 10 has a typographical error.

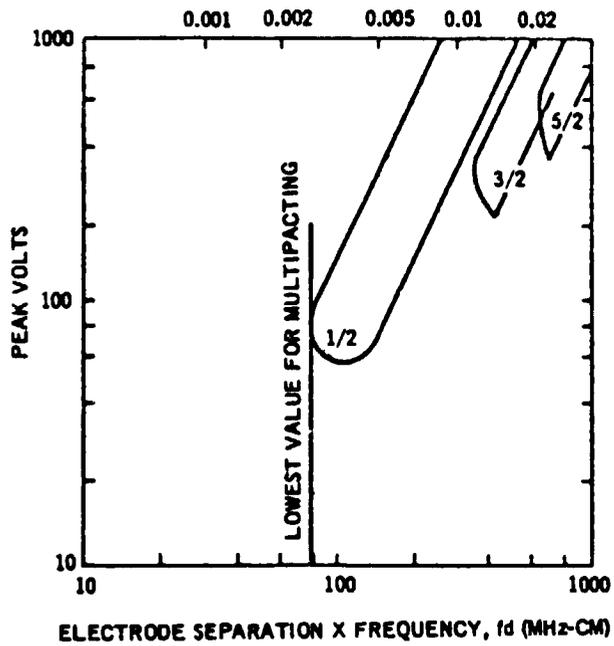


Figure 3-14.- Possible regions of multipacting between parallel plates [from ref. 2].

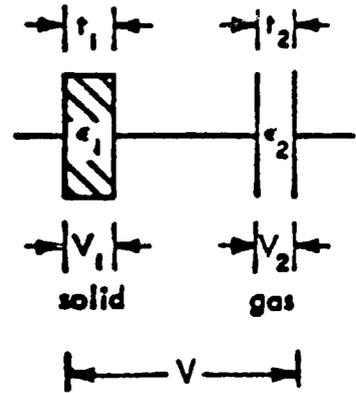


Figure 3-15.- Model for a gas-solid interface.

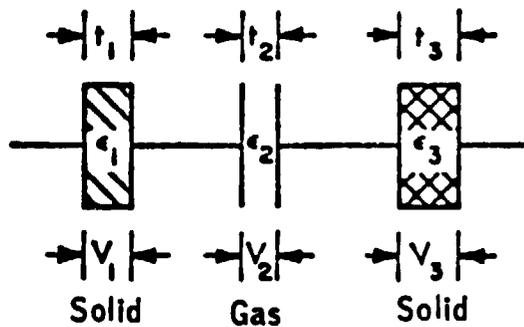


Figure 3-16.- Model for a solid-gas-solid system.

It should be pointed out that in the application of these models it has been assumed that the electrodes are infinite parallel plates. This assumption gives a uniform constant E field between the plates and makes the derivation relatively simple. In a real system such as an insulated wire above a ground plane, the derivation becomes more difficult (ref. 10). These equations can be used to gain qualitative information but should not be used for any quantitative calculations in any real system.

To obtain a better qualitative feel as to the importance of the variables  $\epsilon_1$ ,  $t_1$ , and  $t_2$ , let us put some numbers into the equation

$$V_2 = \frac{V}{\frac{t_1}{t_2 \epsilon_1} + 1} \quad (3-4)$$

Let us assume a system such as that shown in figure 3-17. Of course, for any system other than an infinite plane for both the conductor and the ground plane, the calculations are at best only qualitative.

It will be assumed that the total applied voltage V and the distance from the conductor to the ground t are both held constant. What is of interest is to see how  $V_2/V$  and  $E_2/E$  change as  $t_1/t_2$  changes. The electric field E is what the electric field would be in the air gap if there were no insulation; that is,  $E = \frac{V}{t}$  and the field  $E_2$  is the field in the air gap when there is insulation; that is,  $E_2 = \frac{V_2}{t_2}$ . For the sake of this calculation, assume that  $\epsilon_1 = 5.0$ . If  $t_1/t_2 = 10$ , then  $V_2 = \frac{V}{\frac{10}{5} + 1} = \frac{V}{3}$  and

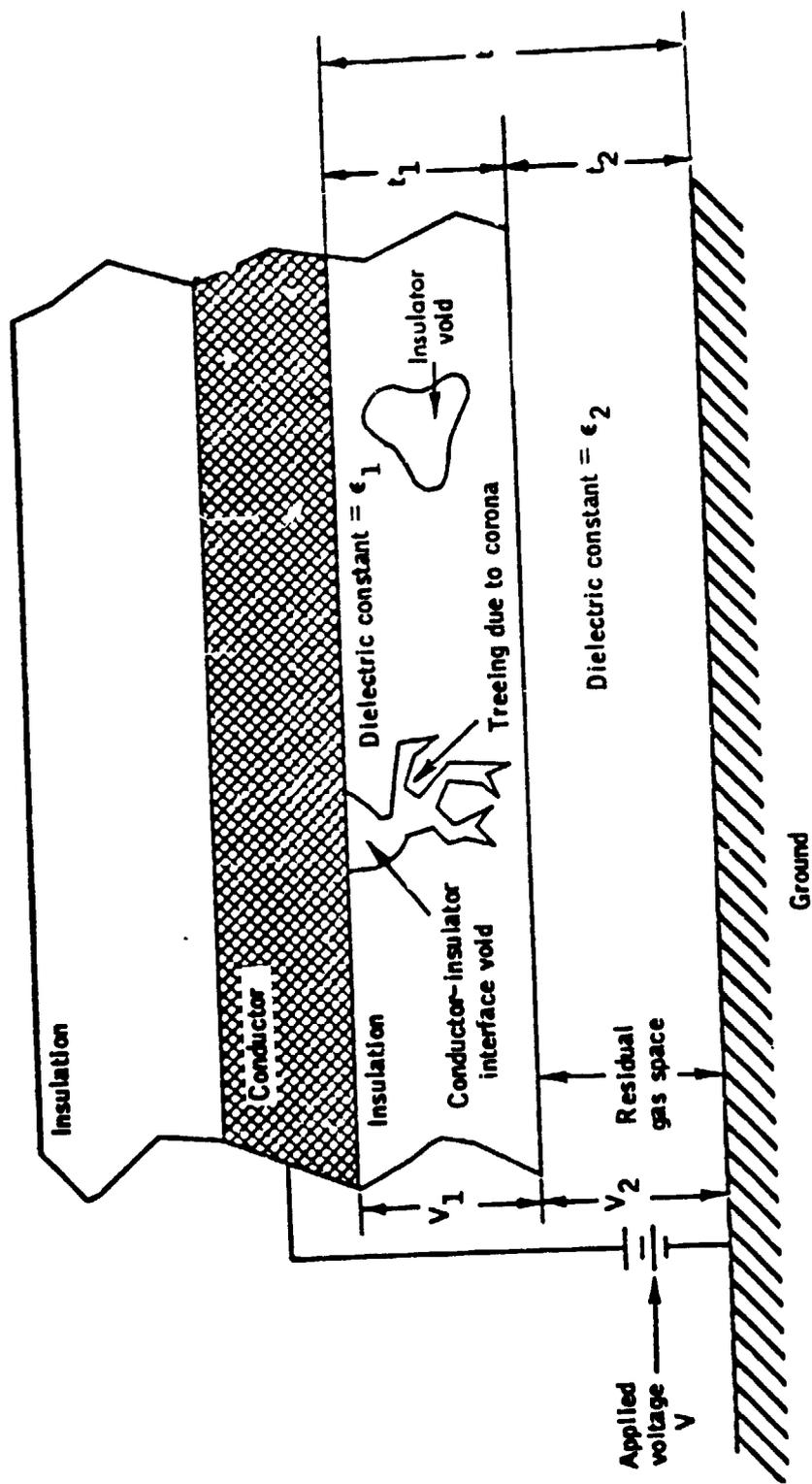


Figure 3-17.- Cross section of typical conductor-insulator system.

$t_1 + t_2 = t = 10t_2 + t_2$ , which gives  $t_2 = \frac{1}{11} t$ .

This results in  $E_2 = \frac{V_2}{t_2} = \frac{(V/3)}{(t/11)} = \left(\frac{11}{3}\right) \left(\frac{V}{t}\right) = 3.7E$ .

Thus,  $\frac{V_2}{V} = 0.33$  and  $E_2/E = 3.7$ . This means that if the insulation is 10 times as thick as the air gap then the voltage drop across the air gap  $V_2$  is one-third of the total applied voltage  $V$  and the electric field in the air gap  $E_2$  is 3.7

times as strong as it would be if there were no insulation. Because it is the electric field and the mean free path that determine the onset of corona, the COV for the system will be lower with the presence of the insulator than without it. This is because the gas will break down long before the solid and it will break down with a lower applied voltage  $V$  than it would have with no insulation.

Putting other values of  $t_1/t_2$  into the equation yields the results shown in table 3-II. What is of interest here are the two extremes of small  $t_1/t_2$  and large  $t_1/t_2$ . For small  $t_1/t_2$ , the voltage drop and the electric field are about the same as if no insulation were present. This would correspond to an insulated wire placed some distance above the ground plane. For large values of  $t_1/t_2$ , the voltage drop becomes very small but the electric field becomes large. The limit to the ratio  $E_2/E$  seems to be 5.0 (the value of the dielectric constant). In fact, if the limit  $t_2 \rightarrow 0$  ( $t_1/t_2 \rightarrow \infty$ ) is taken, the result is

$$V_2 \cong \frac{t_2 \epsilon_1}{t_1} V \left( \text{because } \frac{t_1}{t_2 \epsilon_1} \gg 1 \right) \quad (3-5)$$

and

$$E_2 = \frac{V_2}{t_2} \cong \frac{\epsilon_1}{t_1} V$$

$$\cong \epsilon_1 \frac{V}{t} = \epsilon_1 E \quad (\text{because } t_1 \cong t) \quad (3-6)$$

No matter how small the air gap is, the size of the electric field is limited to the size of what the electric field would have been without the insulation times the dielectric constant. Thus, for small air gaps ( $t_1/t_2$  large) the electric field is large and breakdown will occur at a lower applied voltage than if the insulation were not present. Thus, corona discharge will occur quite readily in voids in the insulation.

TABLE 3-II.- VOLTAGE  $V_2$  AND ELECTRIC FIELD  $E_2$   
FOR DIFFERENT RATIOS OF INSULATOR THICKNESS TO AIR  
GAP THICKNESS  $t_1/t_2$

[ $V$  = total applied voltage;  $E$  = electric field  
that would be in the gas with no insulation]

$t_1/t_2$	$V_2/V$	$E_2/E$
0.1	0.98	1.1
1.0	.83	1.7
5.0	.50	3.0
10.0	.33	3.7
100.0	.048	4.8
1000.0	.00497	4.98

3.4.1.2 Corona discharge in the gas.- When corona does occur in the air gap (voids, etc.), it will build up a charge on the surface of the insulator. This charge builds up until the field produced by it neutralizes the field set up by the applied voltage. At this point, the entire applied voltage is dropped across the insulator. The discharge will not occur again until the accumulated charge has leaked off. If the applied voltage is dc, this may take some time, but it will occur as a result of imperfections in the insulator. When the charge leaks off to a sufficient degree, another discharge will occur. If the applied voltage is ac, the discharge will occur every half cycle.

The pulses of corona produced in this manner have fast rise times (< 0.1 microsecond) and therefore produce a lot of rf noise in the megahertz range. This random radiation can be a major source of interference for sensitive instruments and communications equipment. Over a long period of time (less for ac voltage), these discharges can damage the solid insulator (section 3.4.4).

It is seen to be quite beneficial to eliminate all air gaps and voids, but this is easier said than done.

3.4.1.3 Elimination of the air gap.- From what has been related, it would seem useful, if at all possible, to eliminate the air gap. This can be done either electrically or mechanically.

This can be accomplished electrically by coating all surfaces bordering the air gap with a conducting surface. This surface could be a metalized paint, a metal foil, or a conductive plastic material. The surfaces are then tied together electrically to eliminate the voltage across the air gap. This conductive surface would also smooth out and increase the radius of curvature of the conductors, which would result in a lowering of the electric field intensities. Cables designed for high voltage usually have a conductive coating to accomplish just this purpose. This shielding also helps to protect the insulation from abrasion.

The air gap can be eliminated mechanically by encapsulating (section 3.4.3.1) the entire structure with an organic substance.

#### 3.4.2 Wire Insulation

The proper selection of wire insulation can be crucial to the avoidance of corona breakdown. From the preceding discussion, it is obvious that the insulation should not have any voids and that the dielectric constant should be as small as possible so as to reduce the electric field in the air gaps.

Also, the voltage rating for the insulation in spacecraft should be substantially higher than that required for ground-based operation of the same equipment. This is because of the deterioration effect of corona. It is customary to require a rating twice as high as for ground operation, and not unusual to require ratings five times as high. Some voltage ratings are given in table 3-III.

Historically, there are some other considerations that have not been understood by the designers of electrical and electronic equipment. One common mistake is to select the insulation material strictly on the basis of vendor data without any program of testing. Also, neglecting to consider outgassing, thermal stresses, and high electric field stresses are other common errors.

Outgassing effects can be reduced by choosing insulation that fits snugly onto the conductor and is free of voids both within the insulation and between the insulation and the conductor. Most materials deteriorate when irradiated; however, there is one material that becomes more corona resistant with radiation. When exposed to radiation, irradiated polyethylene will shrink and bond to itself to form a structure with fewer voids.

High electric field intensities can be reduced somewhat by choosing the wire diameter as large as

TABLE 3-III.- ARC-RESISTANCE AND DIELECTRIC-STRENGTH VALUES<sup>a</sup> FOR  
SELECTED INSULATION MATERIALS SUITABLE FOR  
MOLDING, EXTRUDING, OR CASTING

[From ref. 2]

Material	Arc resistance, sec (b)	Dielectric strength, V/mil
Acetal resin copolymer	240	500 to 2100
Acrylic resins	No tracks	400 to 500
Acrylonitrile Butadiene-Styrene	70 to 80	350 to 400
Alkyd molding compound	175 to 235	300 to 350
Cellulose acetate	50 to 310	230 to 265
Cellulose acetate butyrate	Unknown	250 to 400
Ethyl cellulose	60 to 80	800
Diallyl phthalates	105 to 140	350 to 400
Epoxies	120 to 300	300 to 500
Fluorinated ethylene and propylene (copolymer)	>300	500 to 600
Mica-glass bonded	240 to 300+	350 to 400
Neoprene	Unknown	300
Nylons with glass fibers	0 to 150	400 to 550
Phenolic molding compound — unfilled	Tracks	300 to 400
Phenolic molding compound with glass fibers	0.4 to 150	140 to 370
Phenylene oxide resins	Unknown	500
Phenylene oxide resins with glass fibers	120	1020
Polychlorotrifluoroethylene	>360	530
Polyethylene, irradiated	Unknown	2500
Polyolefin	Unknown	1300
Polypropylene with glass fibers	75	300 to 475
Polystyrene (heat resistant)	60 to 135	400 to 600
Polytetrafluoroethylene	>300	480
Polyvinyl chloride	Unknown	750 to 900
Polyvinylidene fluoride	>50	1300
Silicone, mineral-filled	230	390
Styrenes	23 to 40	50 to 425
Viton, fluoroelastomer	Unknown	350

<sup>a</sup>These values are obtained under standard test conditions and may not be obtained in engineering applications.

<sup>b</sup>The arc resistance is the time that a material can endure an arc across its surface before electrical breakdown. This is not related to the ability of the material to endure electrical stress without treeing.

practical. Data on insulated wires can be found in references 10 and 19.

Of course, strict adherence to all ground rules must be traded against other design factors; for example, choosing wire with too large a diameter and too thick an insulation could add a significant amount of weight to the space vehicle. A corona-free piece of equipment that does not perform its function is of no value.

### 3.4.3 Circuit Insulation

Dunbar (ref. 12) states the following reasons for avoiding uninsulated circuitry.

"a. Materials migration is enhanced across open faced circuit boards.

"b. Particles from space and the spacecraft can accumulate on the circuit board and lead to the Malter effect, i.e., momentary short circuits as in a precipitator. In "zero-q" orbital condition, floating debris may short out two adjacent circuits or reduce the effective distance between them, so that corona, tracking, or flashover may occur.

"c. Surface flashover is enhanced.

"d. Some bare metallic surfaces when oxidized, have lower corona and breakdown voltage than a coated or encapsulated surface."

3.4.3.1 Potting or encapsulation.- In potting (encapsulation), the parts of the system are firmly mounted, scrupulously cleaned, and then covered with a potting material that polymerizes in place. The final result is a solid block of potting compound with the high-voltage system completely encased. Polyurethane, silicone rubber, and epoxy resins are frequently used as potting compounds. It is not possible to recommend one or two specific potting compounds that would be suitable for all encapsulation requirements, because the choice is always a compromise between desirable and undesirable

qualities of the material. The designer is urged to consult the materials groups in his organization or the cognizant NASA center for advice in the selection of material. Craig (ref. 20) has published a list of "Apollo preferred materials" that covers such factors as hardness, dimensional change, tensile strength, dielectric constant, et cetera.

Some of the desirable characteristics of a good potting material are as follows.

1. Good bonding to all surfaces
2. Low pouring viscosity to ensure void-free encapsulation (however, it is not recommended to add volatile solvents because of the resultant outgassing problem.)
3. Relatively low amounts of outgassing
4. High shear strength
5. Thermal expansion not too different from parts encapsulated
6. Not too much shrinkage when polymerizing
7. Transparent (or translucent) material to make the location of voids easier.

Most of these properties are predicated on the elimination of voids.

Mechanically rugged components can be successfully potted in rigid epoxy. However, the shrinkage during polymerization and the relatively large (compared to metals, ceramics, etc.) coefficient of thermal expansion result in large mechanical stresses on the encapsulated parts.

More resilient materials such as silicone compounds can be used for encapsulating the more delicate components. These materials while having excellent electrical properties are more prone to outgas in a vacuum than epoxies. Most one-part room-temperature-vulcanizing (RTV) silicones cure by absorbing moisture from the atmosphere and in

the process give off acetic acid. They will not cure in a dry atmosphere or in a sealed container. They are not generally recommended and are only suitable for certain hand-applied conformal coating operations. The preferred RTV compounds are those that give off noncorrosive byproducts such as oximes during cure.

Another successful compound used for encapsulating high-voltage equipment has been the solventless silicone compounds that are cured by adding an activator. After the initial curing, these materials should be given a prolonged high-temperature bake, preferably at reduced pressure. This helps to eliminate some of the volatile constituents that can cause degassing problems. The temperature used should not exceed the maximum storage temperature of the encapsulated parts.

In general, it is recommended to use every conceivable method to eliminate the volatile constituents from the potting materials. One method is to pour the potting material in a vacuum. Another is to use a centrifuge shortly after pouring. A combination of the two methods can be quite effective.

Another potting compound with excellent electrical properties is silicone dielectric gel. It is suitable for impregnating transformer windings and similar applications. This material has very little mechanical rigidity but will not flow under gravity or moderate acceleration forces (such as the linear acceleration of a launch vehicle). It should be noted that the curing of this material can be inhibited by traces of the curing agents (amines) used for epoxies and certain other compounds such as sulfur-vulcanized rubber. Thus, when this material is used, the compatibility of the different materials must be considered. Even the use of an oven in which epoxy had recently been cured has been found to inhibit cure.

The use of foam has been strongly discouraged. Because the foams are lightweight, their use as potting compounds for electrical equipment would seem to be desirable. The foamed packages, however, have failed as the foam outgassed in

space. These failures have usually occurred between 1 hour and 20 days after launch.

Before developing experience with different types of potting compounds, it is difficult to tell which properties will be of paramount importance. For example, in the design for a high-voltage power supply in the Apollo series, shear strength was found to be a decisive factor (ref. 21). The compound RTV-615 was first used to pot the power supply. The material would separate at joints and corners and, when the high voltage was applied, corona and arcing would occur. General Electric then developed (ref. 21) a new compound with greater shear and tear strength. This compound was quite successful. Incidentally, this new material was translucent so that any voids were easy to find.

The main attraction of potting is that it eliminates the air gap. This means that high voltage supplies that would normally break down can function through the critical region. Potting also reduces the need for venting (section 3.4.5) and adds to the mechanical strength of the assembly.

3.4.3.2 Conformal coating.- In conformal coating, the components of the circuit are covered by one or more layers of coating material put on by brushing, spraying, or dipping. Before coating, the parts of the circuit are laid out in a reasonably accessible array, very carefully cleaned, and, if necessary, primed. Dipping is the preferred method because it is most likely to produce a continuous coating without gas pockets. The coating is chosen to have adequate dielectric strength to prevent breakdown from electrical puncturing. Conformal coatings are put on low-voltage circuits, as well as high-voltage ones, to prevent short circuits caused by conducting debris that sometimes appears after launch. The parts are spaced so that the region outside the conformal coating is quickly evacuated when the system is placed in the high vacuum of space. Epoxy resins are the most frequently used materials for conformal coating.

In many cases, conformal coating is followed by potting to take advantage of the strong points of both methods. Of course, care must be taken to ensure good bonding between the two substances.

There is a degree of mechanical protection provided by both the potting and the conformal coating methods in addition to the guarding against electrical breakdown.

3.4.3.3 Effect of potting on multipaction.- If the circuit compartment is filled with a foam-in-place material (like Eccofoam), the breakdown voltage can be effectively tripled over the no-foam value. The foam restricts the motion of the charged particles. This method, however, results in a need for complete retuning of the circuit. This is probably the only place where the use of foam is recommended.

#### 3.4.4 Insulator Deterioration Caused by Corona

When dealing with insulators, it is often found that the dielectric strength is much lower than expected. The dielectric strength drops with increasing time of application of voltage and is usually lower for ac voltage than for dc voltage. The higher the frequency of the ac, the faster the rate of deterioration. Over long periods, the dielectric may fail at electric fields not much higher than would be required to break down an equivalent layer of air.

These phenomena are usually the result of corona discharges occurring in voids in the solid or in the vicinity of electrodes on the surface (section 3.4.1). These discharges will chemically degrade the solid. This can lead to the production of a different chemical species whose electrical losses are high enough to cause thermal runaway. Or the discharges can result in a gradual erosion until the intrinsic strength of the material is exceeded in some spot.

The mechanical properties can also deteriorate to the extent that any mechanical forces present can cause electrical failure. For example, many

polymers can become brittle enough to crack, which can lead directly to failure. Materials under mechanical strain may also undergo "stress-cracking" or "ozone-cutting." These effects are the cutting of polymer chains by electrical discharges or their byproducts. Corona discharge in air forms ozone and oxides of nitrogen. These gases will then react with the insulator and surrounding materials to produce undesirable nitrates and other compounds. One example of the damaging effect of these reactions is the deterioration of polyethylene insulation by means of the formation of a surface residue of oxalic acid.

3.4.4.1 Treeing.- One of the progressive-type failures caused by corona is called "treeing." This condition usually begins at a lesion in the insulation and then progresses as a series of branched channels through the insulating layer. The lesion can be produced by an excessive electric field or by the impact of charged particles from an electrical discharge in a void in the insulation. The growth of these channels occurs because the electrical stress at the ends of the channels is so concentrated that the intrinsic insulation strength is locally exceeded. The similarity of the appearance of the branch channels (fig. 3-17) to the branches of a tree gives rise to the name.

It has been observed that trees grow at lower peak ac voltages than dc voltages. Because ac voltage produces a discharge every half cycle (section 3.4.1.2) while dc discharges occur much less frequently, this is not too surprising.

Certain insulating materials (such as polyethylene, polypropylene, etc.) are especially susceptible to this type of failure. The only ways to avoid treeing failure is to keep the applied voltage from producing electric fields strong enough to initiate corona and to eliminate voids. The electric field can be kept down by eliminating sharp corners and points.

3.4.4.2 Tracking.- After a corona discharge or arc-over has occurred in an air gap or void, a permanent

conducting path will be formed on the surface of some solid dielectrics. The formation of this track is governed by the type of material and the existence of moisture or other contaminants on the surface. If such a path of low resistance is formed, then subsequent breakdowns will occur more readily and lead to further insulation breakdown. In the case of a dc-applied voltage, the accumulated charge after one discharge will leak off much more rapidly than before the track was formed. This would allow many more discharges per unit time. In choosing insulation, the ability of the material to resist tracking should be considered.

3.4.4.3 Creepage.- When discharges take place at surfaces, another type of phenomenon may occur that is known as high-voltage creepage. This can occur when relatively high electric fields are present and tangential to the surface of the dielectric. An example would be two sharp-edged electrodes placed on a sheet of insulating material. The applied voltage may not be high enough to cause immediate breakdown but could be sufficient to cause discharges at the sharp edges of the electrodes. If this is the case, then gradual deterioration of the dielectric in the region of the discharges may occur. These regions could become partially conducting owing to carbonization or oxidation followed by absorption of moisture. Such conducting areas could act as extensions of the electrodes and the discharges would "creep" over the dielectric surfaces. If the conducting areas finally met, an arc would form and the system would fail. Even if a system is initially free of discharges, contamination of the surfaces with dust and moisture can often cause local high electric fields and accompanying discharges. These discharges can then lead to creepage and eventual failure.

3.4.4.4 Insulation life.- If there were no weight restrictions on the insulating material, the simplest way of prolonging its life, even to many years, would be to specify that the maximum electric fields within the material be kept very small; for example, less than 800 V/mm (about 20 V/mil). However, spacecraft designers have to

minimize weight and volume and the long-life aspect must sometimes be compromised.

The functional life of an insulator is dependent upon its electrical properties, the applied voltage stress and its duration, the materials-application workmanship, and the ambient temperature.

Life characteristics of insulating materials are usually derived from curves that plot  $\log$  (life) versus reciprocal absolute temperature. Dunbar (ref. 12) has modified this to having a plot of life time vs. voltage stress (fig. 3-18) for RTV-60 (a silicone rubber product). Another plot (fig. 3-19) shows the life characteristic of various thicknesses of RTV-60 in an ionizing or near-ionizing atmosphere.

Dunbar states, "plots like these should be made for each insulating material by the insulation design engineer before the material is accepted for a high voltage application. These plots are normally based on data obtained from a qualified test laboratory."

#### 3.4.5 Venting and Degassing

When the vacuum in space drops to  $10^{-6}$  torr or less, it becomes an excellent insulator. The dielectric strength of a hard vacuum is about  $5 \times 10^5$  V/cm, which is about 20 times as great as that of dry air at sea level. This is because at these low pressures there are few charge carriers and the mean free path far exceeds the gap between the electrodes.

If the spacecraft contained a high-voltage power supply that was not needed until the high-vacuum environment was reached, then it would seem attractive to leave it off through the launch period. In this way, the critical region would be avoided and the high voltage could be turned on after adequate venting.

This is fine in principle but there are some practical problems. Almost all high-voltage

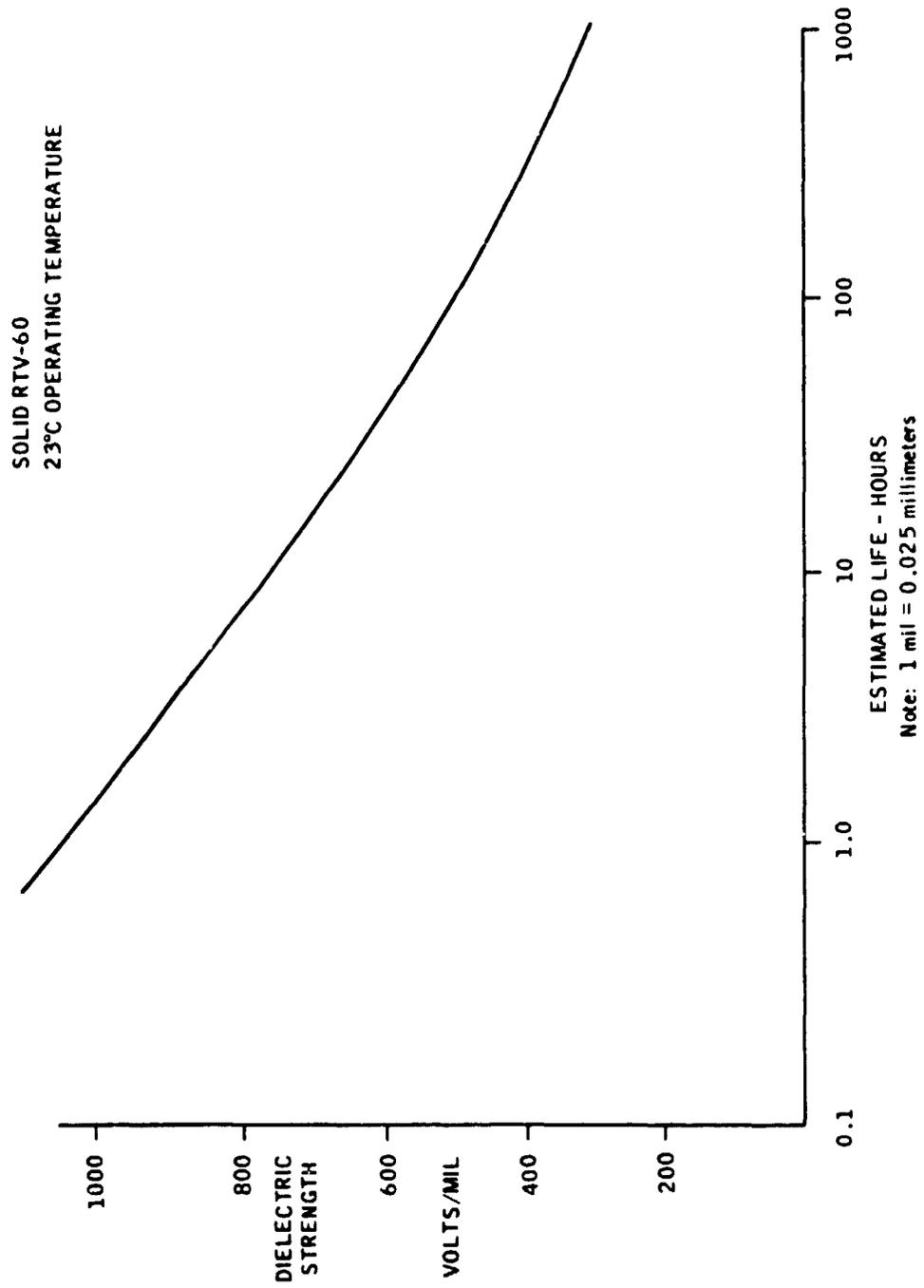


Figure 3-18.- Effect of voltage on life of RTV-60 [from ref. 12].

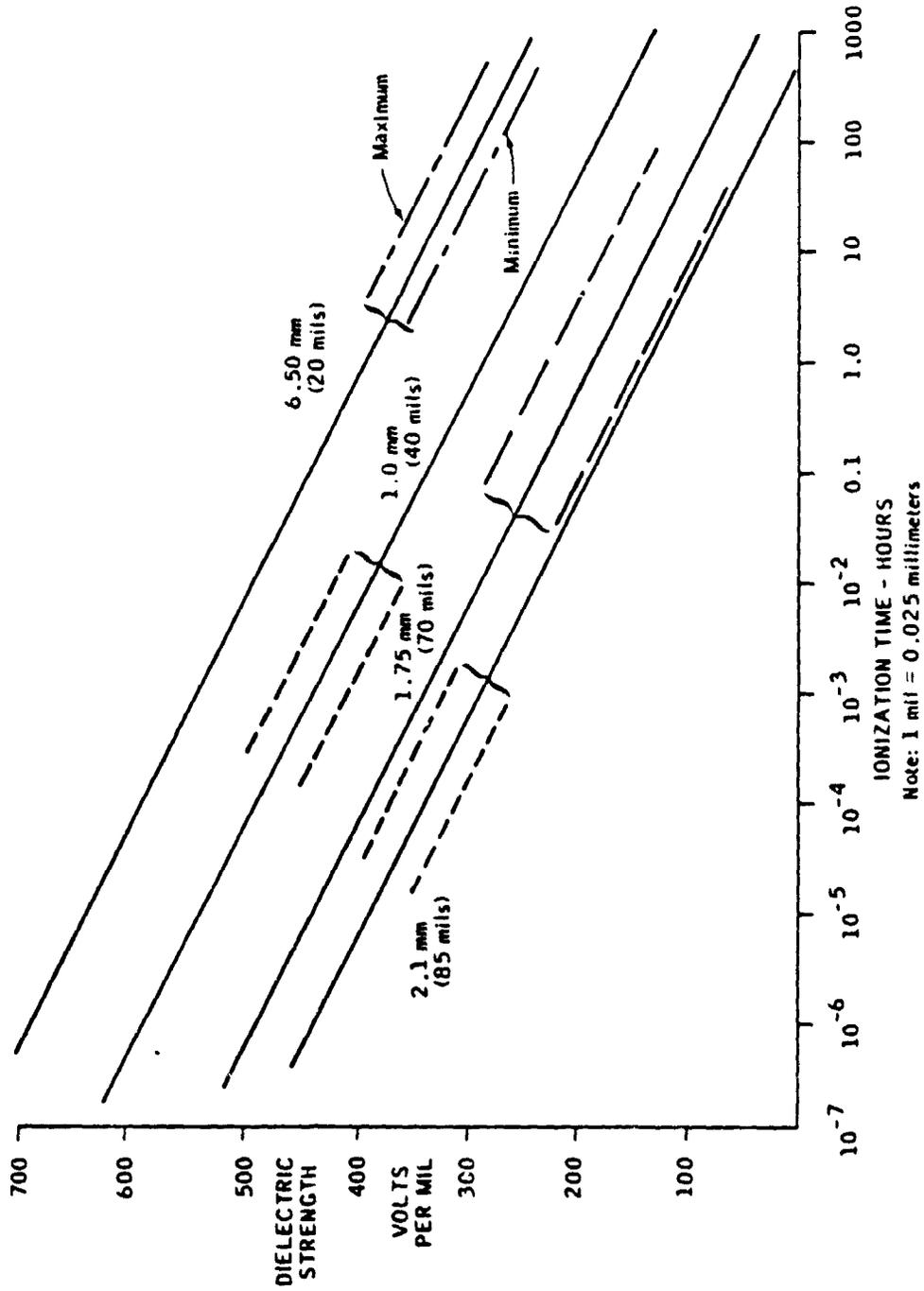


Figure 3-19.- Dielectric strength of RTV-60 as a function of ionization time [from ref. 12].

systems must be enclosed to some extent. On the ground, they must be protected from dust, dirt, and mechanical damage; and in flight it is often necessary to shield the components from sunlight and charged particles from space. Holes must be placed in strategic locations to vent these enclosures adequately. The pressure near the high-voltage components must fall very rapidly when the pressure outside the enclosure is reduced. Paul and Burrowbridge (ref. 2) give two convenient rules of thumb: "First, the pressure near the high voltage system should drop to approximately 37 percent of its initial value in one second when the pressure outside the enclosure is suddenly reduced to a very low value; and second, an alternative and roughly equivalent to the first, is that for every liter of volume in the enclosure there should be one square centimeter of area of evacuation port." The first rule can be checked experimentally and the second can be calculated (ref. 22). However, in using the second rule, care must be taken not to underestimate the evacuation time when the exit path of the gas molecules is tortuous or has narrow channels. If a box is contained within a box that is in another box, for example, then the evacuation time for the inner box may be prohibitively long.

Even with proper venting, the gas pressure may never leave the critical region. A spacecraft tends to have an atmosphere of its own produced by many sources.

1. Outgassing of organic materials (potting compounds, etc.)
2. Sublimation of different surfaces
3. Trapped air within the components
4. Gas-filled voids in insulation
5. Spacecraft leakage gases
6. Gas from the propulsion or control jets
7. Gas from the jettisoning of waste products

The last three effects can perhaps be mitigated by careful placement of the instrument package in relation to these sources. Source 2 could probably be lessened through proper treatment of the surfaces. Sources 1, 3, and 4 can be controlled by careful choice of insulating material and proper handling of the fabrication stages.

Unfortunately, there has not been a study of the effect on corona discharge of the outgassing of the potting materials. Craig (ref. 20), Leger (ref. 23), and Campbell et al. (ref. 24) have prepared lists of materials giving the percentage weight loss and percentage volatile condensable materials (VCM). Leger (ref. 25) is also in the process of calculating the contamination effects of the potting materials used on the Space Shuttle and its payloads. These lists can be of some help but it would certainly be desirable if similar lists could be made for corona discharge effects.

With all the variables present, it is difficult to predict when it would be safe to turn on the high-voltage supply. If it is turned on while the pressure is still in the critical region, the results could be disastrous. The only way to be certain that this does not happen is to measure the pressure near the high-voltage supply. When the pressure is low enough, the power supply can be turned on.

#### 3.4.6 Causes of Voids

It has been seen in previous sections that voids can have a deleterious effect on high-voltage systems because corona discharges within them cause the insulation to be degraded. Also, they can hold the pressure in the critical region by slowly degassing. In two of the sections that follow, it will be seen that voids can also cause connectors to arc over and transformers to fail. Thus the elimination of voids seems to be a necessity for the proper functioning of electronic equipment in space. Of course, before voids can be prevented, their causes must be understood.

3.4.6.1 Wire insulation and voids.- Two types of voids can occur with wire insulation. One is a defect in the insulation itself and, through corona discharge, can lead to a failure of the insulation and arcing. The other type is an air space between the conductor and its insulation. This gap can be caused by improper handling of the wire.

To illustrate this problem, high-voltage wire with a conformal coating will be used as an example. This development is after Dunbar (ref. 12). Assume that a high-voltage lead (wire) has been soldered at both ends and that a conformal coat has been applied onto the entire circuit (fig. 3-20). Note that the high-voltage wire has an outer shield (braid). This braid has the functions of smoothing out the electric field and of electrical shielding.

When the circuit is allowed to be at room pressure for 3 to 6 months, the inside and outside pressures become stabilized. The air trapped within the strands of wire and the insulated braid can create problems during a space mission. The conformal insulation seals the wire ends and all the normal outgassing ports along the length of the wire. If the system is not evacuated before exposure to space vacuum, there can exist a pressure differential of 1 atmosphere (760 mm Hg) between the braid and the outer jacket. In vacuum, the outer jacket (conformal coating) will be forced to expand at the weakest point by the internal pressure (fig. 3-21). Heat and mechanical stress will eventually create a small rupture in the outer jacket. When this happens, the pressure will equalize as the braid out-gasses. This release of gas will create a transient pressure in the vicinity of the rupture and any high-voltage circuits in line with the rupture could be momentarily pressurized. This could cause corona or arcing. However, the rupture is most likely to occur near terminals. Here the outgassing can create more serious problems. Once the braid has outgassed, a pressure differential can exist between the braid and the conductor. If the bond between the insulation and the wire has been weakened in some

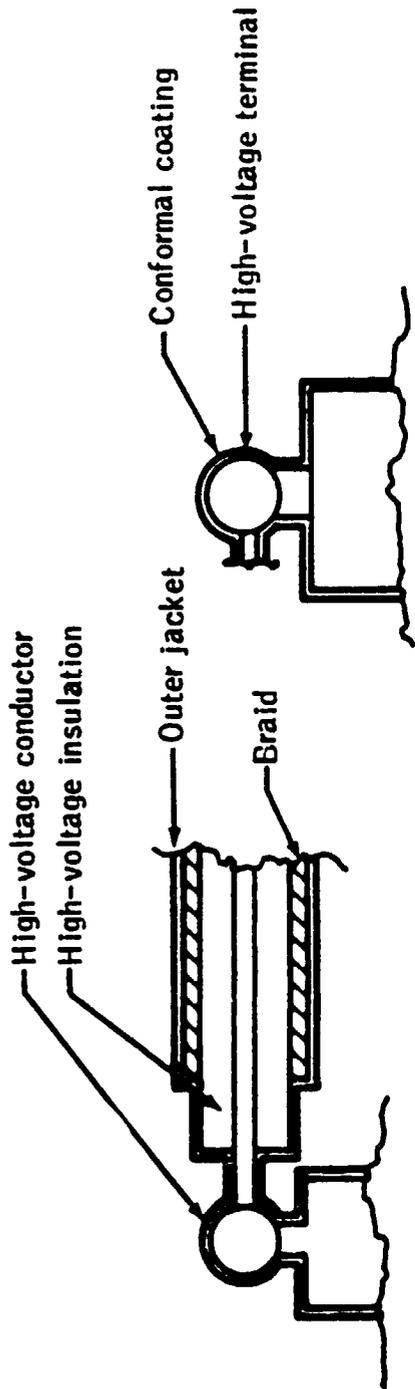


Figure 3-20.- High-voltage conductor at 1 atmosphere.

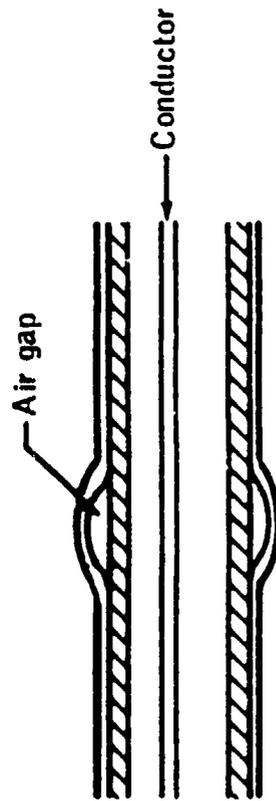


Figure 3-21.- Outer jacket rupture.

fashion, then the insulation can pull away from the conductor as shown in figure 3-22. Any separation results in a small air gap (void) between the high-voltage conductor and the grounded braid via the high-voltage insulation. As the gas slowly leaks out, the pressure in the void will decrease and eventually a corona discharge will begin. If the corona discharge lasts for at least 100 hours, the wire insulation will begin to tree and eventually a short circuit will result.

This catastrophe can be averted if the braid and outer jacket exert enough pressure to prevent delamination of the insulation from the conductor. The existence and cause of flows in the conformal coating must be investigated and a deliberate effort made to eliminate them. Flows can be caused and aggravated by two basic methods: abrasion and flexure. Abrasion will cause the outer jacket to be thinner in a particular spot. The jacket could then expand more easily at this spot than elsewhere along the unscarred material. Flexure, however, is a more probable cause. The wire can be bent, twisted or flexed several times during installation in the spacecraft or during the testing and handling before installation. Wherever the flexing occurs, the insulation bonds to the conductor are weakened. This can result in failure of the voltage system as explained previously. Outgassing from unsealed wire strands will usually occur through the wire terminations. This outgassing can cause a momentary corona or voltage breakdown at the termination. This can create an EMI in the readout data, which may be difficult to differentiate from the valid data.

Sometimes an outgassing port is made through the conformal coating to the center conductor. The wire may take as long as 100 hours to outgas. In figure 3-23, the angle of the port  $\alpha$  must be as nearly perpendicular to the field lines as possible. If  $\alpha$  is greater than  $30^\circ$ , tracking may result.

A special high-voltage wire has been developed to prevent an electric field from being built up across any voids between the conductor and the

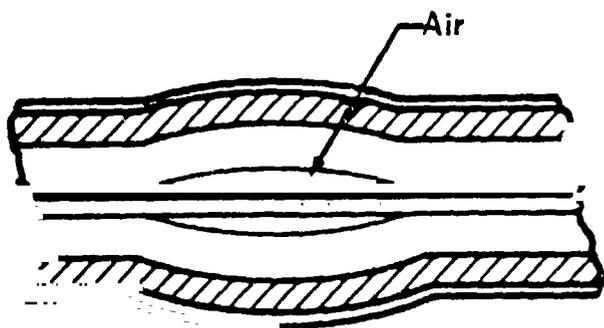


Figure 3-22.- Center conductor delamination.

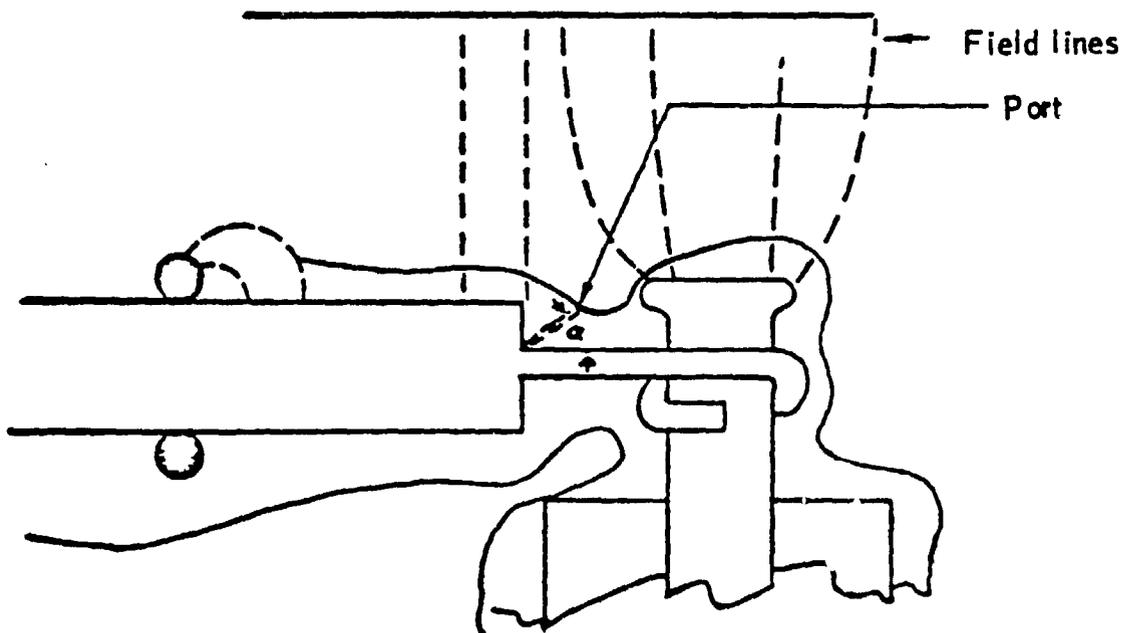


Figure 3-23.- Vented high-voltage wire.

insulator. This special wire has a conductive coating of a material like graphite applied to the inner surface of the insulator. The conductive coating fills the voids and is in contact with the conductor. Thus, no electric field can be built up in the voids.

Stranded wire has advantages over solid wire. It is not as easily damaged by flexing and it provides more reliability under vibration than the solid wire. But voids between the strands of wire are inevitable and the electric field associated with a voltage applied to the stranded inner conductor is must greater than that of the round solid wire. The reason for this second condition is that the electric field depends upon the radius of the strands (section 3.3.1.3). Also, solid wire requires less venting than stranded wire.

Thus, solid wire is recommended for use when flexing is not a requirement and vibration is not a problem. If stranded wire is used, choose wire with the inner conductive coating.

Whichever wire is chosen, try to minimize the amount of flexing and stressing. Try to prevent the overstressing of the wire by avoiding pulling or the use of small radius bends. A good practice is to coil the high-voltage wire around the power-supply case and then to tape it in place until it is required for test or connection. The wire should be long enough so the section to be connected is not required to be abnormally flexed or twisted during test.

3.4.6.2 Connectors and degassing.- High-voltage connectors have given so much breakdown trouble that there is a tendency not to use them at all.. All the junction points are soldered with the possible exception of very high voltages. Even then rudimentary connectors such as that shown in figure 3-24 are used (ref. 2) The unit requiring 15 kilovolts rests directly on the rounded central stub where the voltage is developed, thus obviating the need for leads.

Of course, some equally successful designers do use connectors. The key to success is adequate

venting. No gas can be allowed to be trapped in the connector body in such a way that it can leak out slowly. If this happens, a critical pressure environment can result for the high-voltage leads in the connector long after one would have expected all gas to have diffused into space. Connectors are vented by drilling holes through the body and insulation to permit ready egress of the gas. An adequately vented connector is the lower one shown in figure 3-25.

This figure also shows a failed connector. This was a commercial connector that was simply potted after the connection was made. This made a nearly gastight seal around the electrical leads. The gas slowly leaked out during the vacuum test. When the pressure around the leads became low enough, a breakdown occurred. The arc-over drew large currents and eventually destroyed the connector.

3.4.6.3 Circuit insulation and voids.- As with the wire insulation, there are two types of voids to be eliminated - those internal to the potting material and those between the potting material and the components that are encapsulated. The internal voids can be eliminated only through a good deal of effort. This effort must be expended because, if any voids do exist, the material will deteriorate and breakdown will ensue (section 3.4). Great care must be taken in the choice of potting material. The attributes of a good potting material are outlined in section 3.4.3.1. Dunbar (ref. 12) outlines certain procedures that must be followed if electrical breakdown is to be avoided. These steps are as follows.

"Encapsulation - An adequately encapsulated high voltage circuit has all the interspace between electrical components, wires, circuit boards and ground planes filled with a homogeneous solid insulation. This process must have the following qualities:

"a. All components, boards, and wiring must be cleaned of particles, grease, finger prints, non-cohesive materials, and solder flux prior to encapsulation.

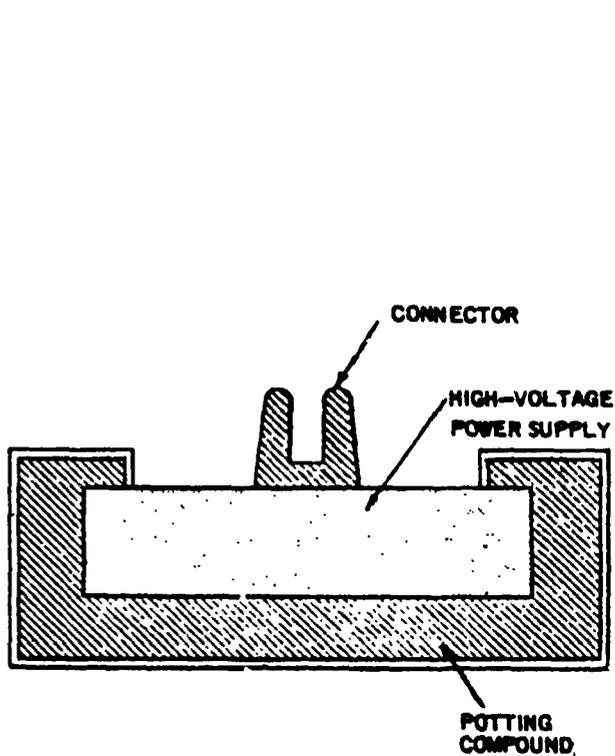


Figure 3-24.- Direct-contact 15-kilovolt assembly [from ref. 2].

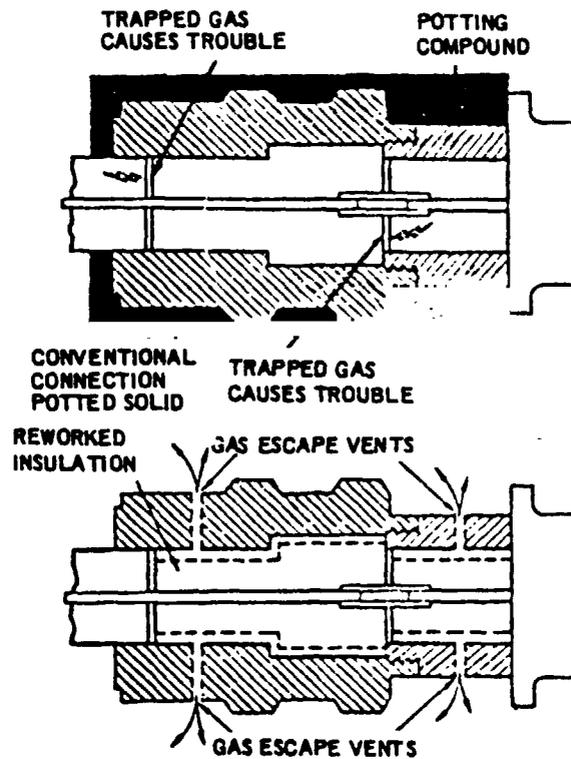


Figure 3-25.- Vented electrical connectors avoid trapped gas [from ref. 2].

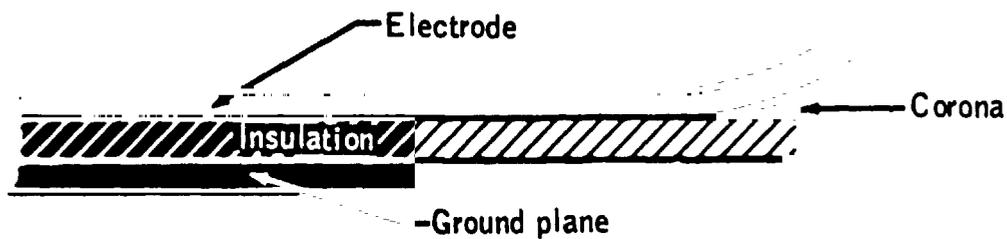


Figure 3-26.- Corona caused by electrode pulling away from insulation.

"b. The materials must be checked for bonding to the components by laboratory testing. The tests should include: temperature cycling, high voltage stress during temperature cycling, and shelf life stand prior to temperature cycling. A common error is to evaluate a material in a soft flexible aluminum dish and then expect it to hold its properties in a solid structural application.

"c. The encapsulated volume should be kept small without jeopardizing the electrical integrity of the encapsulant. When large volumes are required, the volume should be long and narrow. This reduces the probability of internal mechanical stresses which can result in component-to-component cracks. Volumes with physical dimensions greater than one inch wide and two inches deep, and several inches long may have many internal cracks.

"d. Solid encapsulation must be void-free to be effective. This especially includes voids near the ground plane as well as the high voltage components and circuits. Three methods of void-free encapsulation are vacuum impregnation, centrifugal motion, or a combination of those two.

"e. Final encapsulation of high voltage interconnecting wiring and terminal parts must be done very carefully. The wires must be properly fixtured so they are not pulled or twisted or otherwise disturbed during or following the proper cure.

"The encapsulant must bond to all the other materials. This is especially true of like materials. Sometimes a poor bond can exist between a newly applied insulation and an insulation of the same type which has been oxidized or has shelf degradation."

When filling a space between two electrodes, care must be taken so that the space is entirely filled and the mechanical layout does not lead to one of the electrodes pulling away from the insulation. If the edges do creep away as shown in figure 3-26, corona will occur at the place marked by an

arrow. This corona will attack the material and lead to electrical breakdown.

3.4.6.4 Transformers and voids.- Byers (ref. 26) has given certain design procedures for producing corona-free high-voltage transformers. He sums up the most important items as follows.

"(1) Choose a core of sufficient size and of the proper construction, (2) select wire of sufficient size for reliability, (3) select an interlayer insulating material compatible with the impregnating material to be used, and (4) choose impregnating and encapsulating materials which are compatible with each other and with core coating, wire insulation, and the interlayer insulating material."

The designer for spacecraft is always trying to save on size and weight. Thus, it might seem attractive to design transformers with as small wire as possible. Let us compare No. 42 magnet wire with No. 46 magnet wire. The insulation thickness of No. 42 double-thick polymethane-coated wire is 0.000250 inch and the insulation material is rated at 1500 V/mil. This gives No. 42 wire insulation a breakdown voltage of 350 volts. No. 46 (0.0016 inch) wire has an insulation thickness of 0.00150 inch, giving it a breakdown voltage of about 225 volts. The smaller wire has greater electric fields produced for a given voltage and yet it has more potential for breakdown than the larger wire. Also, the smaller the magnet wire, the greater the chances are of damaging the insulation or stretching the fine copper wire during winding. A reasonable choice of wire size has to be made.

Byers found that Teflon-coated wire would not bond to the impregnating epoxy. This left voids in the material which could lead to electrical breakdown. The wire coatings of choice were double-thick polyurethane and double-thick nylon-jacketed polyurethane. Another advantage of the polyurethane-insulated wire was that the wire can be stripped in solder, thus eliminating chemicals that, if not completely removed before

encapsulation, could cause failure of the joint at some later date.

It was also found that voids were produced when Teflon tape was used as the interlayer insulation. There was a complete lack of adhesion between the interlayer Teflon tape and the potting material.

A transformer using an open-weave Dacron tape for the interlayer insulating material, polyurethane-coated wire, and an epoxy filler was found to produce no voids. Cleanliness was found to be exceedingly important. No oils (caused by fingerprints, etc.) greases, or silicones should be allowed to contaminate the different parts of the transformer. These contaminants prevent proper bonding between materials.

Failure of an OSO-IV satellite (ref. 27) while in orbit was felt to be due to the use of Teflon tape in the manufacture of a transformer. Because of the nonbonding between the tape and the filling material, a void was formed. This void led to electrical breakdown.

### 3.4.7 Temperature Effects

3.4.7.1 Temperature cycling.- Spacecraft electronics must operate over a fairly broad range of temperatures. During this change in temperatures, there can be a great deal of mechanical stress in the insulation. The stress occurs when the material has a different coefficient of thermal expansion than the components. Low temperatures can crack or craze insulation when parts contract at unequal rates. Cracked insulation can continue to operate properly at low temperature because there is little outgassing at that time. As the temperature increases, however, the newly exposed insulation surface may outgas enough to slightly pressurize the crack. If the crack is in a high electric field and the pressure is high enough, corona will result. If the corona continues, it will heat the insulation and increase the outgassing rate. This process could lead to thermal runaway; that is, an interlocked cycle of the raised gas pressure causing heating and the

heating causing more outgassing. Eventually a massive corona discharge or arc will follow, which could damage the high-voltage circuit.

3.4.7.2 Hot spots.- It is the temperature in the area of highest electric field, rather than the ambient temperature, that affects corona formation. "Hot spots" increase the outgassing rate of the insulation. This generates voids, minute cracks, and small pressurized enclosed volumes that enhance corona and arc-over.

These hot spots can be the result of contaminants on the surface of the electrodes or insulation. These contaminants are things like dust particles, oxides, and salts that are present in the air during assembly, storage, transportation, and launch. The breakdown voltage between contaminated electrodes is up to an order of magnitude lower than that between pure metals or alloys.

These hot spots can become hot enough (500° C) to cause thermionic emission. This would further enhance the discharge and lead to catastrophic breakdown sooner.

3.4.7.3 High temperatures.- High temperatures can be very damaging to insulation. When insulation is exposed to an overtemperature (i.e., temperature above its rated temperature), it will:

1. Outgas and pressurize voids and volumes.
2. Become more conductive, which increases the probability of surface creepage and flashover.
3. Lose part of its integrity. The insulation dielectric strength decreases as temperature increases, creating cracking and treeing and more chance of breakdown or arcing.
4. Suffer degradation caused by atomic oxygen, which is more active than ozone. At temperatures above 450° F, ozone disassociates into atomic oxygen.

5. Not allow the dielectric to dissipate the heat that is generated internally. This will cause the dielectric to be even hotter than ambient temperature.

6. Cause the material to melt or decompose (thermal breakdown) if the temperature of the dielectric becomes high enough.

There are several processes that can generate internal heat in a dielectric placed in an electric field. Three of the more important ones are as follows.

1. The flow of ionic currents
2. Interaction of electronic currents with the lattice
3. The displacement of bound ions or dipoles in an ac field

The amount of heat generated by one or more of these mechanisms increases with the applied voltage.

In the development of the B-2707 airplane, it was realized that the electric wire insulation would be exposed to temperatures approaching 500° F caused by aerodynamic heating and the Joule heating from the load current. Dunbar (ref. 19) states, "Insulated wire is difficult to treat analytically from a corona standpoint because of proprietary materials and processes used in making wire, and because of the secondary corona products from high temperatures. Furthermore, early identification of corona-free wire types is essential to further development of the electrical system. For these reasons, extensive corona tests were conducted on insulated wires using a heated oven within a vacuum chamber."

Dunbar placed seven twisted wires (tests have shown (ref. 10) that twisted wires have a higher COV than spaced wires) in a 500° F oven held at a pressure equivalent to 80,000 feet altitude. The procedure followed by Dunbar (ref. 19) is provided here. "The bare conductors were energized to

ionize the gas surrounding the test specimens. The test-specimen wires were tested for corona once every 12 to 24 hours, with the ionizing wires turned off. The life test was terminated at the end of 172 hours when the corona onset voltage of one wire pair dropped to that of spaced bare conductors."

The lowest COV for the wires was about 550 volts before dropping to the COV for the bare conductors. "During visual inspection following the tests the following characteristic changes were observed:

"Sample 1: 22 mil Teflon insulation (BMS 13-31): insulation destroyed, 3/4 inch of conductor exposure.

"Sample 2: 8 mil H-film insulation (Dupont 99B): Binders have evaporated, exposing several punctures between H-film wraps. H-film surface etched on surfaces facing ionizing conductors.

"Sample 3: 14.5 mil H-film and Teflon insulation (Gore SST-2): Many minute punctures, color is stable, and insulation appears good otherwise.

"Sample 4: Conductors used to produce ionization.

"Sample 5: 15 mil H-film and Teflon insulation (Super temp-5): This sample had no apparent discoloration or punctures.

"Sample 6: 18.5 mil proprietary insulation (Revere SST-2): One large puncture, color leaching.

"Sample 7: 12 mil H-film and Teflon insulation (Super temp-3): The Teflon insulations were fused together in several places.

"Sample 8: Glass braid and Teflon insulation (Prestolite hotelec): The glass braid was difficult to inspect. Color

leaching was observed in the heated sections."

For temperatures up to 500° F, Dunbar recommends that at least 30 mils of Teflon insulation or equivalent must be provided between wires. Boeing BMS 13-31 Teflon wire has 44 mils of insulation. Dunbar reports that this wire can withstand a continuous 690 volts rms at 500° F without corona formation. However, it is not good practice to operate any wire at its maximum allowable COV limit. Any transient would be able to initiate corona.

In choosing wire insulation, the CEV must also be taken into consideration. At altitudes above 60,000 feet and temperatures above 250° F, the CEV is approximately 20 volts less than the COV. The wire insulation chosen should have a maximum voltage rating well above the CEV.

For temperatures above 500° F, metal-sheathed, solid-ceramic-insulated wire is recommended. Tests at Boeing (ref. 28) on wire to be used for instrumentation and control have shown that:

"(1) Organic insulation has limited life in temperatures over 500° F;

"(2) Inorganic insulators, other than ceramic, have high conductance at high temperatures;

"(3) Fibrous or spaced-beaded insulation within a solid or braided sheath will become plated with oxides of the sheath and/or conductor at temperatures above 1000° F, resulting in short circuits;

"(4) Solid metal sheaths protected the wire from ionized gases and foreign materials and structurally contained the ceramic insulation.

"Several solid-ceramic insulated thermocouple wires have been tested to temperatures of 2000° F, both at sea level and in vacuum. No corona was present below 1000 volts ac when these wires were properly terminated. Parasitic voltages are generated between conductors of ceramic-insulated

thermocouple wires heated to temperatures exceeding 500° F. These voltages add to the signal attenuation caused by increased conductor resistance and lowered insulation resistance. However, the parasitic voltages can be made insignificant by using large wires. It was found that No. 22 gage conductors in metal sheaths produced less than two percent reading error even when 20 feet of the circuit was heated to 1500° F."

Another effect of high temperatures is to lower the altitude at which COV occurs.

Dunbar (ref. 19) shows that  $N_2 = N_1 \left( \frac{T_1}{T_2} \right)$  where  $T$  is the absolute temperature and  $N$  is the number of moles.

The ideal gas law,  $PV = NRT$ , was used to derive this equation. This equation shows that a rise in temperature ( $T_1 \rightarrow T_2$ ) at a constant pressure will cause a decrease in the number of moles of a gas ( $N_1 \rightarrow N_2$ ). A decrease in the density of the gas (i.e., a decrease in the number of moles of a gas) will result in an increase in the mean free path. This means that the COV will decrease at a given pressure if this pressure is above the Paschen minimum when the temperature rises.

3 4.7.4 High temperature and contaminants.- The atmosphere of the electronics can be contaminated by the release of adsorbed gases and from the oxidation of nearby spacecraft structures. Above 500° C, this contamination can significantly reduce the COV. Figure 3-27 shows a minimum COV of 2 volts for molybdenum electrodes. The dielectric strength of air has essentially been reduced to zero! It does not seem to be the high temperature that causes this drastic reduction in the COV, but the contaminant molybdenum trioxide. Some other electrodes in air do not degrade nearly so badly for 1000° C plus; for example, zirconium wires go from about 300 volts to about 200 volts minimum COV in a temperature change of from 27° C to 1100° C. Also, the introduction of molybdenum trioxide into the atmosphere of nickel-clad copper wires

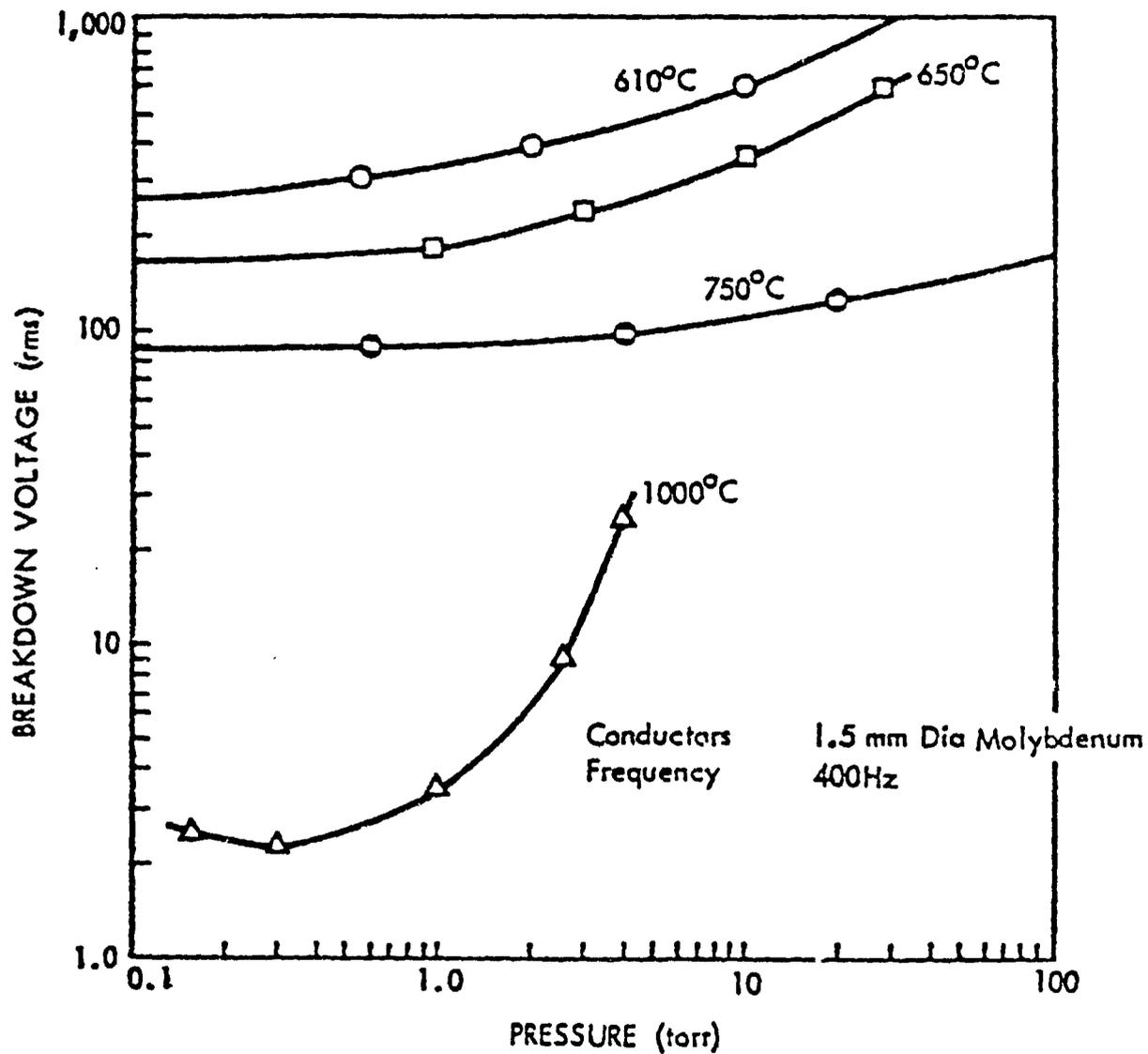


Figure 3-27.- Molybdenum wires spaced 6 millimeters in air [from ref. 10].

reduces the minimum COV to about 20 volts at 520° C as shown in figure 3-28.

This is only one contaminant. With the complexity of the spacecraft environment, there is the possibility that other kinds of contaminants could reduce the COV just as dramatically as does molybdenum trioxide.

Because titanium was a part of the B-2707 airplane, Dunbar (ref. 19) decided to see if it would create any special corona problems at high temperatures. The presence of titanium in the atmosphere did not significantly lower the COV in going from 77° F to 500° F.

### 3.5 PRESSURIZED AND OIL-FILLED CONTAINERS

Pressurization is attractive because the high-voltage system can be sealed inside a known atmosphere. Thus, if the system is corona-free on the bench, it would also be corona-free in space.

The usual gas is water-free and is maintained at a pressure slightly greater than sea-level pressure. Some of the more popular gases are given (ref. 2) in table 3-IV. Notice that helium and argon are not listed. Experience with these gases shows that they are not effective in preventing electrical breakdown. Most of the gases listed in table 3-IV are nontoxic.

As attractive as pressurization seems, it has not been extensively used in orbital flights. The main problem is in keeping the gas leakage sufficiently small in the longer orbital flights. One method has been to provide a reservoir to replace the gas lost by leakage. The pressurization method has found some favor, however, in many sounding-rocket programs.

Oil-filled containers seem to have some advantages over both the pressurized container and the encapsulated one. They should not be as hard to seal as the gas-filled ones and they may not have the deterioration problems of the solid

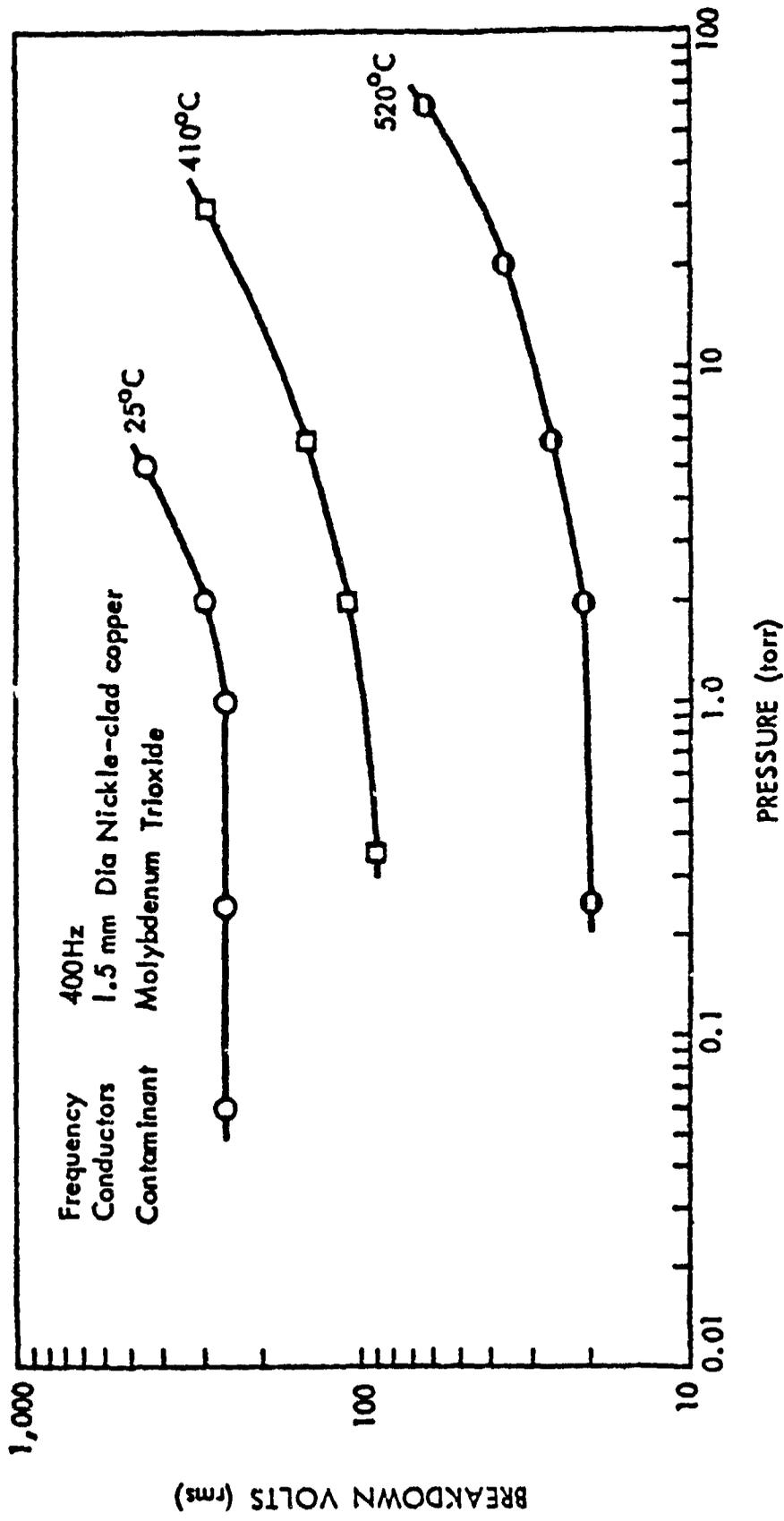


Figure 3-28.- Nickel-clad copper wires spaced 6 millimeters in air [from ref. 10].

TABLE 3-IV.- GASES SUITABLE FOR HIGH-VOLTAGE SYSTEMS IN HERMETICALLY SEALED CONTAINERS  
 (From ref. 2)

Gas	Properties of gases at 760 mm Hg									
	Formula	Density at 0° C, g/liter (lb/ft <sup>3</sup> )	Molecular weight	Melting point, °C	Boiling point, °C	Relative dielectric strength (H <sub>2</sub> = 1)	Dielectric constant	Specific gravity (Air = 1)	Flammability	
Air	--	1.2929 (0.08018)	28.952	--	-198.0	--	<sup>a</sup> 1.000590	1.00000	No	
Hydrogen	H <sub>2</sub>	.08988 (.005611)	2.0156	-259.14	-252.8	--	<sup>b</sup> 1.000264	.06952	Yes	
Nitrogen	N <sub>2</sub>	1.2506 (.07807)	28.016	-209.86	-195.8	1	<sup>a</sup> 1.000580	.96724	No	
Sulfur hexafluoride	SF <sub>6</sub>	6.700 (.417)	146.06	--	-63.8	2.3	<sup>c</sup> 1.00191	5.19	No	
Dichlorodifluoroethane	CCl <sub>2</sub> F <sub>2</sub>	<sup>d</sup> 6.33 (.395)	120.93	-158	-29.79	2.46	<sup>e</sup> 1.0016	--	No	
Perfluoropropane	C <sub>3</sub> F <sub>8</sub>	--	188.02	-160	-36.7	2.2	--	--	No	
Octafluorocyclobutane	C <sub>4</sub> F <sub>8</sub>	<sup>e</sup> 9.62 (.601)	200.04	-41.4	-5.85	2.86	<sup>f</sup> 1.0034	7.323	No	
Perfluorobutane	C <sub>4</sub> F <sub>10</sub>	--	238.03	-80.0	-2.0	2.8	--	--	No	
Chloropentafluoroethane	C <sub>2</sub> ClF <sub>5</sub>	<sup>d</sup> 8.37 (.522)	154.48	-106	-38.7	2.54	<sup>g</sup> 1.0018	--	No	
Dichlorotetrafluoroethane	C <sub>2</sub> Cl <sub>2</sub> F <sub>4</sub>	<sup>d</sup> 7.83 (.489)	170.94	-94	3.77	3.34	<sup>h</sup> 1.0021	--	No	
Hexafluoroethane	C <sub>2</sub> F <sub>6</sub>	<sup>d</sup> 9.01 (.562)	138.02	-100.6	-78.2	2.02	<sup>i</sup> 1.0020	--	No	
Tetrafluoroethane	CF <sub>4</sub>	<sup>d</sup> 7.52	88.01	-184	-127.96	1.06	<sup>j</sup> 1.0006	--	No	

<sup>a</sup>At 0° C and 3 × 10<sup>6</sup> Hz.

<sup>b</sup>At 0° C and 2 × 10<sup>6</sup> Hz.

<sup>c</sup>At 27.5° C and 708 mm Hg.

<sup>d</sup>Saturated vapor at boiling point.

<sup>e</sup>At 29° C (0.5 atm).

<sup>f</sup>At 0° C.

<sup>g</sup>At 27.4° C (0.5 atm).

<sup>h</sup>0.5 atm at 26.8° C.

<sup>i</sup>At 23° C.

<sup>j</sup>1.2 atm at 24.6° C.

dielectric. After all, oil-filled transformers are used on high-tension lines quite successfully. However, if they ever did leak, the contamination problems could be serious. Also, under vacuum and low-temperature conditions, bubbles form in the oil. These bubbles are just corona discharges looking for a place to happen. This is believed to be the failure mechanism for an oil-filled capacitor in the Apollo lunar module tracking light. While under low-temperature conditions, the liquid shrank away from the top. This left a space inside the can under the terminals which then arced over.

## 4.0 PHENOMENA ASSOCIATED WITH ELECTROSTATIC VOLTAGE

### 4.1 PRODUCTION OF ELECTROSTATIC VOLTAGE

#### 4.1.1 Triboelectric Charging

Triboelectric charging occurs whenever two dissimilar materials are placed in contact with each other and then separated. One material pulls electrons from the other leaving the first with a negative charge and the second with a positive charge. An example of this occurs when a hard rubber comb is rubbed with cat fur. When an aircraft flies through precipitation containing ice crystals, the ice crystals lose electrons to the airframe. Thus the aircraft ends up with a negative potential caused by the accumulation of negative charge. The potential of an aircraft flying in precipitation will rise until the corona threshold potential is exceeded. At this point, corona discharge will begin and the corona discharge current will be equal to the charging current. It is a good approximation to regard the triboelectric-charging mechanism as equivalent to a constant current source.

#### 4.1.2 Rocket Motor and Jet Engine Charging

Before any conclusive measurements on rockets were made, it was felt that the rocket engine could have one of three effects on the electrostatic potential of the spacecraft.

1. If the engines were capable of charging the vehicle to potentials above the vehicle threshold potential, then corona discharges and EMI would accompany each launch.

2. If the conductivity of the exhaust was sufficient to limit the vehicle to some value below the corona threshold potential, then there would be no corona discharges or associated EMI caused by engine charging. Other charging sources could, however, still cause corona discharge.

3. If the ionized rocket exhaust was so effective a discharger that the vehicle potential was held below corona threshold even when other charging sources were present, then the rocket engine would tend to alleviate, rather than aggravate, the vehicle charging problem.

From measurements on the Titan III-C rocket (ref. 29), it is now clear that possibility 3 is the closest to reality (see section 4.5).

Jet engines correspond to the second possibility (section 4.5). The crucial parameter for this difference between rockets and jet engines seems to be the temperature. When the afterburners on a jet engine are turned on, it behaves exactly as a rocket engine, as far as electrostatic charging is concerned. The mechanisms of engine charging are still in a great deal of doubt. For a discussion of some of these mechanisms, see references 30 and 31.

## 4.2 DISCHARGING EFFECTS

### 4.2.1 Corona Discharge

4.2.1.1 Discharge to the air.- When the corona discharges occur to the air, the same sort of physical processes are going on as with the corona discharge between two plates. The main difference, of course, is that there is only one solid metal electrode in the case of discharge to the air.

As with the case for two electrodes, for a discharge to take place into the air it is necessary that the field be sufficiently high that an electron (on the average) can acquire ionizing energy between collisions. In other words, the energy of the electron depends on the electric field and the mean free path. This means that the discharge will take place at places with the smallest radii of curvature; that is, the small radius concentrates the field lines (section 3.3.1.3). As a rule, the discharge will occur

from burrs and imperfections (unless dischargers are present) on the extremities of the aircraft.

For the discharge to begin, there has to be at least one free electron (which was probably produced by cosmic rays). The action of the electrostatically produced field moves this electron from the point and causes it to collide with air molecules, which become ionized. This produces additional electrons that in turn are accelerated by the field. This electron avalanche continues to propagate and grow until it reaches a region at some distance from the point where the field is too low to permit ionization by collision and where the electrons are slowed sufficiently that they attach to oxygen molecules to produce  $O_2^-$  ions. The  $O_2^-$  ions are much less mobile than the electrons and they may be considered to be stationary as far as the discharge processes are concerned. The relatively stationary cloud of  $O_2^-$  ions tends to reduce the field between itself and the point. This reduces the distance to which the next avalanche can propagate. On the other hand, the cloud of positive ions left behind by the movement of the electrons tends to increase the field between itself and the point. Thus, avalanches are initiated more readily in this region. Many of the free electrons necessary for avalanche formation are probably supplied by photoemission from the negative point. The discharge continues as a series of successive avalanches.

Each avalanche propagates a shorter distance than the last as the inner limit of the cloud of  $O_2^-$  ions approaches the discharge point. Meanwhile, the positive ions are being drawn into the point. Finally, the negative space charge reduces the field near the discharge point to such an extent that ionization by collision is no longer possible. When this occurs, the discharge is choked off. At sea-level pressures, this process only takes about 0.2 microsecond. Under the action of the wind and the applied electric field, the ions are gradually swept away from the discharge point. The whole process then repeats itself.

The potential at which discharge occurs decreases with an increase in altitude. The reasons for this behavior are exactly the same as for the case of two electrodes; that is, the mean free path increases with decreasing density.

The discharges occur as a series of discrete impulses of short duration and rapid rise time. They therefore produce rf noise over a broad spectrum. This interference may disable radio receiving systems and, in some cases, may induce spurious pulses in the electronic systems controlling stage sequencing and vehicle guidance.

- 4.2.1.2 Discharge caused by improper bonding.- Another place the effect of vehicle charging can be detrimental is where the conducting sections of the vehicle are not bonded together. For example, consider a rocket vehicle that is charged triboelectrically on the forward surfaces and discharged through corona from the skirt at the aft end. If the forward section is not electrically connected to the aft section, charge acquired on the forward section cannot flow to the aft section unless the potential difference between the sections becomes large enough for a spark discharge to occur. The electrical isolation could occur as a result of improper electrical bonding at the interface of two sections. These spark discharges can be quite energetic, because the capacitance between the sections may be several thousand picofarads and the sparkover voltage may be several kilovolts. Furthermore, the spark discharge will seek the easiest electrical path between the sections. If there is some electrical wiring routed across this gap, it is possible that the spark will travel through a shorter gap from the front section to the wiring, through the wiring, and then through another short spark gap to the aft section. This, of course, would put a tremendous noise pulse on any data line. Also, there is the possibility that these spark discharges could fire electroexplosive devices.

Proper bonding between sections of the spacecraft is a must.

#### 4.2.2 Streamers from Insulator.

Vehicle charging can also be detrimental when the vehicle skin is composed of dielectric or of dielectric-coated sections. These sections can become charged triboelectrically from passage through ice crystals or other particulate matter. In contrast with the metal skin, the charge cannot flow away from the point where it is deposited. Charge thus accumulates on the surface until the electric field along the surface is large enough to support a streamer discharge over the dielectric surface to a metal structure nearby. However, if the dielectric strength of the insulator is exceeded before the streamer occurs, then the charge is relieved by a spark discharge that punctures the dielectric and travels to an underlying conductor. Streamer discharges, like spark discharges, seek the easiest path to the vehicle structure.

These discharges can generate a great deal of rf interference.

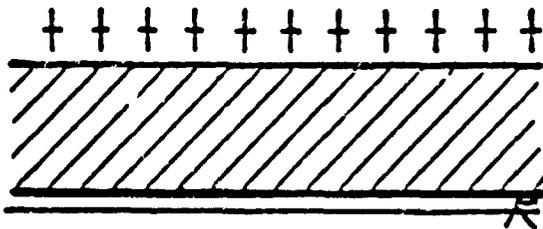
#### 4.2.3 Windshields

Because windshields are made of an insulating material, the same sort of effects occur with them as with other dielectric materials. Streamer discharge from windshields is a source of rf noise.

Puncture of windshields has occurred as a result of the discharge of charge accumulation through the windshield. This can only occur if the windshield has a metallic electrode on the interior. Two types of deicers are shown in figure 4-1. The wire type tends to concentrate the electric field lines more than the other type, thus making the windshield more puncture-prone.

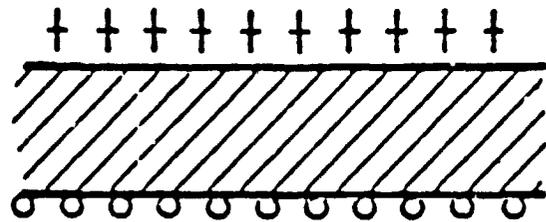
For further information on windshields, see reference 32.

Charge



Conductive coating

(a) Coated type.



Wire

(b) Wire type.

(Dashed lines are the electric field lines.)

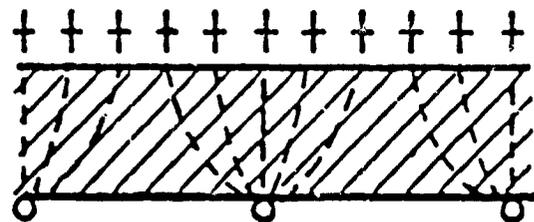
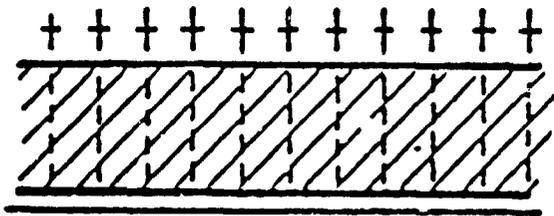


Figure 4-1.- Deicers for aircraft windshields.

#### 4.2.4 Staging Effects

It had been conjectured that electrostatic discharges could occur between stages as they separated. In fact, it was shown that the separation of two dissimilar objects could cause substantial voltage difference between the bodies (ref. 33). However, experiments by Vance and Nanevich (ref. 34) have shown that the two parts of the staging vehicle will be electrically connected through the conductive exhaust plume as long as the motor exhaust plume plays on the expended stage. Thus, it does not seem conceivable that significant differences in potential (i.e., more than a few tens of volts) can be developed between separating sections during a staging event in which the upstage motor is ignited at or before the time of stage separation.

#### 4.2.5 Impact Noise

The rf noise produced by corona discharge and its streaming from the skin of the aircraft is known historically as precipitation static. The reason, of course, is that, when the airplane was flown through precipitation-containing clouds, the rf noise would occur.

There is a third type of noise included in the category of precipitation static which for a long time was overshadowed by the two sources mentioned previously. This third type is known as impact noise. This noise was found to be produced by the individual precipitation particles impinging on the aircraft. It consists of overlapping step-fronted pulses produced by the individual precipitation particles as they acquire charge upon impact in a region of reciprocal antenna field (ref. 35).

## 4.3 SUPPRESSION OF rf NOISE

### 4.3.1 Coating of the Airframe

One of the first efforts to eliminate precipitation-static interference was an attempt to eliminate the charging of the airframe (ref. 35). It was well known that all materials could be arranged into a triboelectric series. In this series, materials higher in the series tend to charge positively when brought into contact with materials below them in the series. Neighboring materials in the triboelectric series tend to charge one another less than do widely separated materials. For this reason, it was felt that it might be possible to eliminate or at least minimize aircraft charging through a suitable choice of paint. Attempts along these lines were completely unsuccessful. Triboelectric charging is a surface phenomenon and a thin film of oil is sufficient to completely destroy any desirable properties that a coating might have. Also, the position of a material in the triboelectric series tends to be a function of dielectric constant, and the dielectric constant of ice varies with temperature. Thus, it would be very difficult to find a coating suitable for all weather conditions.

### 4.3.2 Coating of Insulators and Windshields

It has been found that a high-resistance conductive coating over the dielectric surface is quite effective in eliminating streamer noise. The conductive coating drains away the charge as rapidly as it arrives and prevents the electrostatic potential buildup that produces the streamer discharges. The coatings (ref. 36) used for nontransparent dielectrics are usually opaque and have a surface conductivity on the order of 0.1 megohm.

Most windshields are made of one of either glass or acrylic plastics. Glass has a lower surface resistance ( $\sim 10^{12}$  ohms) than the acrylics ( $\sim 10^{16}$  ohms). This is attributed to the somewhat-open

silica network in glass, which allows hydration. It has been shown that a surface resistance of  $10^6$  ohms is probably sufficient to bleed off accumulating charge.

The plastic windshield is more sensitive to breakdown than glass. It will develop a higher charge because of its higher resistance and it has a lower dielectric strength. Also, no permanent antistatic coating is yet available. There are some multiple-layered coatings under development that seem to hold some promise.

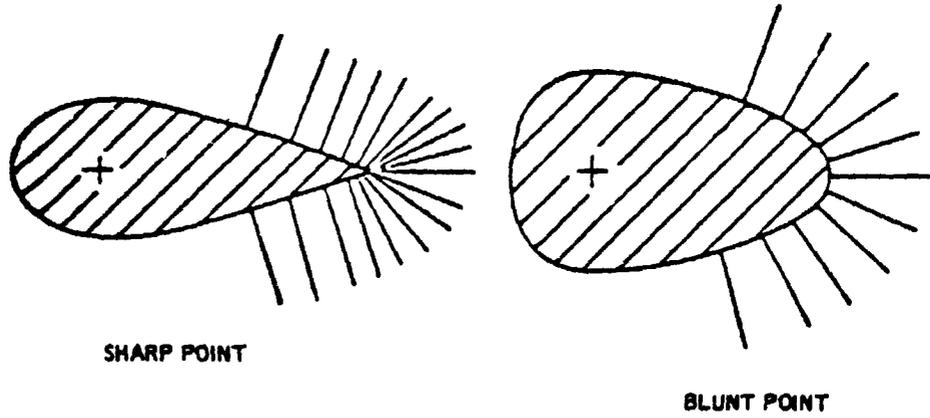
The principal coating presently used for glass outer panels is stannous oxide. This material can be fused into the glass exterior surface to sufficient depth that erosion should not seriously reduce the conductivity of the external surface coating during the life of the windshield.

#### 4.3.3 Dischargers

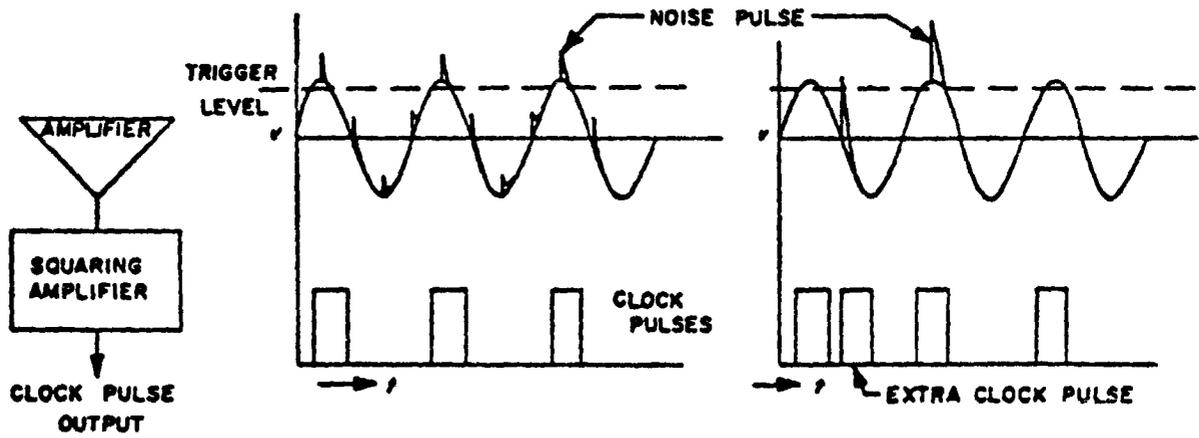
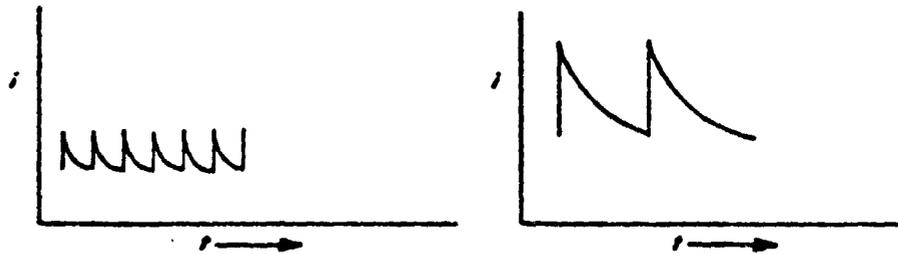
The sharper the point from which the discharge occurs, the smaller the voltage discharge, and, therefore, the smaller the interference pulses that may be coupled into data lines. This effect can spell the difference between malfunction and proper function. An example of the difference this can make is shown in figure 4-2. The larger corona pulses have generated an extra clock pulse. This is not a heuristic example but one that actually happened (ref. 37).

It is then seen to be of great utility to reduce the level of the corona discharge. This can be accomplished through the use of dischargers. Some of the proposed dischargers have been (ref. 35) the block and squirter, the biased discharger, flame dischargers, electron gun discharge tubes, and direct thermionic emitters. Tanner and Manevich (ref. 35) report decoupled dischargers with a noise reduction of greater than 50 decibels. Wick dischargers have been used quite extensively, but they tend to disintegrate very rapidly at the speeds of turbojet aircraft (ref. 35).

DISCHARGE  
POINT  
GEOMETRY



DISCHARGE  
CURRENT  
PULSES



RFI - DIGITAL MALFUNCTION EXAMPLE

Figure 4-2.- Corona rf interference (RFI) effects.

#### 4.3.4 Changing the Coupling Between the Antenna and the Dischargers

When it is only the communications link that is of importance, a great deal of noise suppression can occur through the proper choice of the antenna and its placement. The equivalent noise field of a loop antenna can be reduced by mounting it near the end of an airplane member (ref. 35). The correct placement can reduce the noise factor by 25 decibels. At least 25 decibels noise suppression can also be obtained with dipole antennas if two of them are correctly placed and balanced.

#### 4.3.5 Blanking the Input

In contrast to the preceding mentioned methods of precipitation-static reduction, the blanker approach attacks the problem at the receiver terminals. In principle, the blanker is an ideal switch that is placed ahead of the receiver so as to completely suppress both signal and noise whenever a noise pulse appears. Unfortunately, there are serious theoretical and practical problems with the blanker (ref. 35). It is not seriously considered as a means for noise suppression.

#### 4.4 DISCHARGE EFFECTS ON ELECTROEXPLOSIVE DEVICES

Electroexplosive devices in the rocket can be set off by corona discharges. Unbonded sections present a real danger because of the intensity of the spark and because the spark may discharge through an electroexplosive device. Streamer discharges can also be energetic enough to ignite one of these devices. Vance et al. (ref. 38) report that all three discharge mechanisms (corona, sparking, and streamer discharges) can fire the Apollo electric initiator in the pin-to-case mode. They made an extensive review of all the initiators in the Apollo spacecraft and made the following conclusions and recommendations.

"a. Triboelectric charging from ice crystals encountered in the lower atmosphere during launch appears to be the most detrimental source of vehicle electrification insofar as the Apollo initiators are concerned.

"b. Information available on rocket engine charging is presently insufficient to predict the effect of this charging mechanism accurately.

"c. At altitudes above 100 kilometers where the vehicle is immersed in the ionosphere or in the solar electron-proton flux, ambient ionization is adequate to limit vehicle potentials to below 1000 volts even in the presence of moderate charging from other mechanisms.

"d. Adequate bonding between all sections of the vehicle will eliminate hazardous spark discharges between the sections.

"e. If bonding is adequate, the most hazardous result of vehicle electrification will probably be the production of streamer discharges from the command module (or boost cover) surface to the LES [launch escape system] tower legs and to the CM/SM [command module/service module] umbilicus.

"f. Adequate shielding can eliminate the hazard of electrostatic discharges to the initiator system.

"g. The only shielding system known that ensures immunity to electrostatic discharges in the atmosphere as well as in space is one that completely encloses the initiator system in a continuous metallic cover.

"h. The present Apollo initiator, even if it meets the initiator specification, is not immune to electrostatic initiation in the environment encountered by the Apollo [spacecraft] unless it is within a completely closed shield system.

"i. The numerous modifications and design revisions that have been incorporated or may be required to make the initiator system immune to

electrostatic or RF initiation may compromise the reliability of the overall system."

#### 4.5 TITAN III-C FLIGHT PROFILE

##### 4.5.1 Instrumentation

The instruments measured the following parameters during the flight of the test vehicle (ref. 29).

1. Instantaneous vehicle potential
2. Charging rate
3. Impinging-particle count
4. Streamer discharge pulse rate frequency (PRF)
5. Streamer discharge current
6. Ambient electron density

An electric-field meter system is used to measure vehicle potential. A charging patch located on the nose of the rocket is used to measure the charging produced by impinging dust or precipitation particles only. The generated streamer pulses were measured by charging a small insulating region on the vehicle nose. The electronic circuitry used for the streamer studies included provisions for measuring the streamer current and for counting the number of streamers generated. The langmuir probes are for studies during orbit injection; the placement of these probes on the rocket is shown in figures 4-3 and 4-4.

##### 4.5.2 Flight Results

The Titan III experiments were quite successful. There were two separate flights, the Titan III-C-20 and III-C-21. The flight of III-C-20 was in clear weather and the III-C-21 was launched in rain. As far as the electrostatic measurement

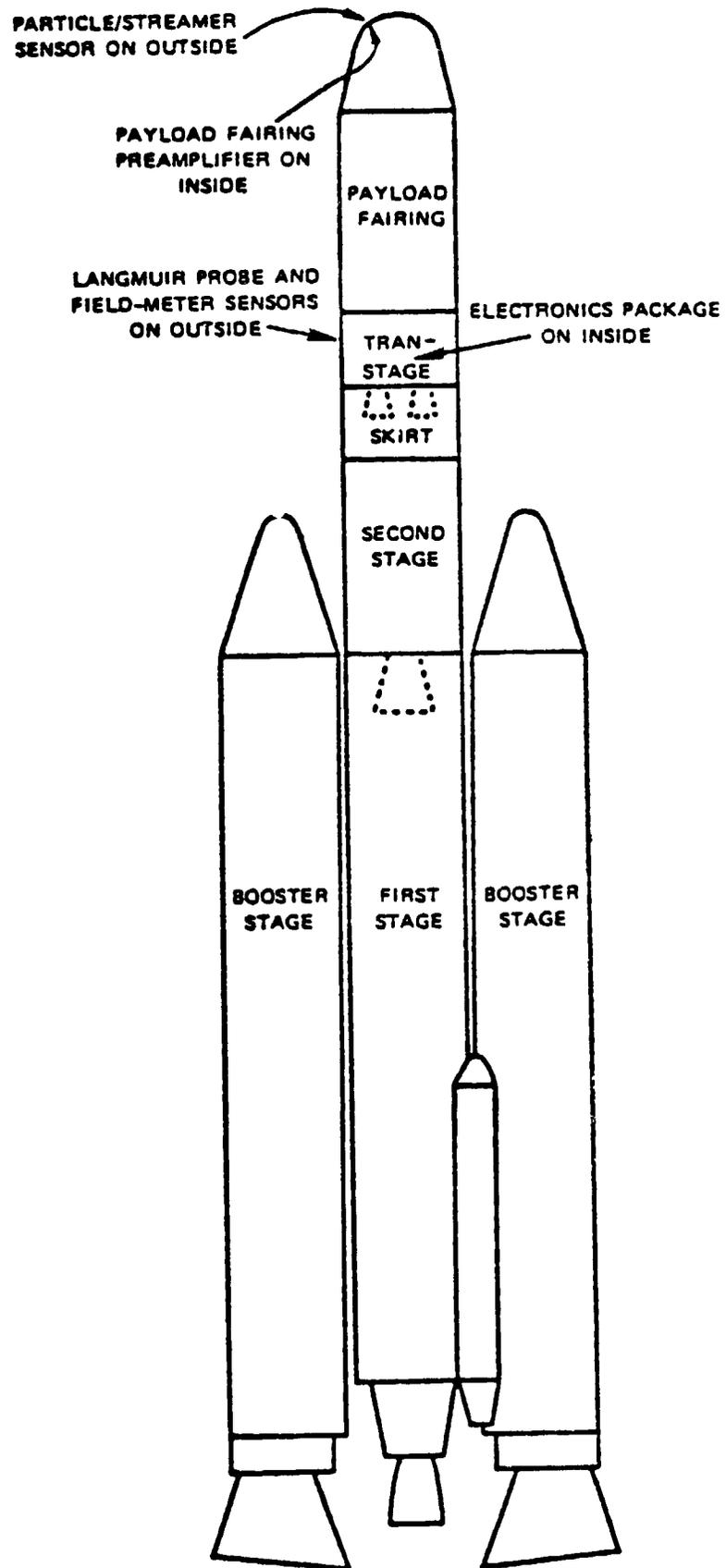


Figure 4-3.- Sketch of Titan III-C test vehicle.

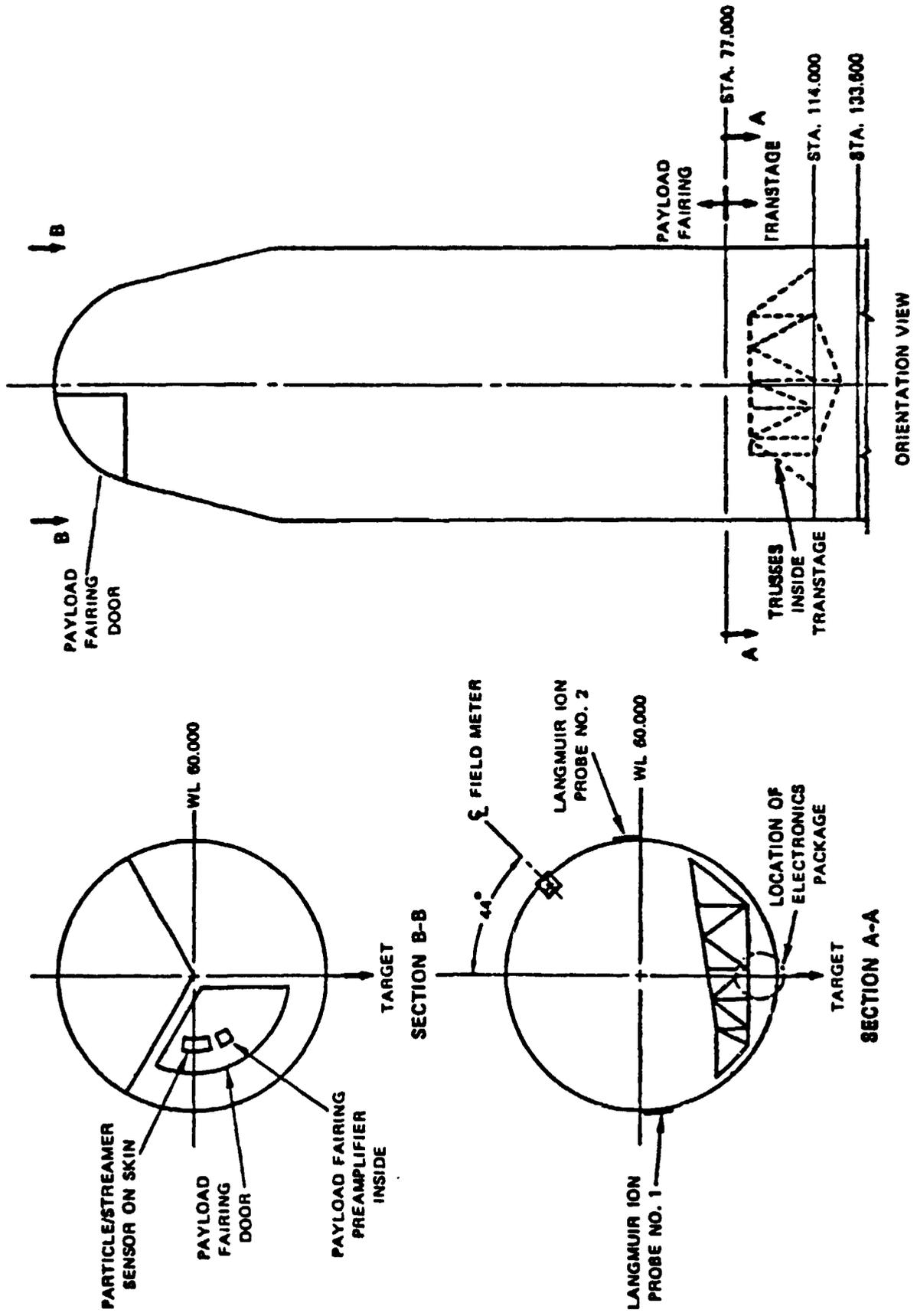


Figure 4-4.- Location of instrumentation and sensors on Titan III-C test vehicle.

experiment was concerned, this was ideal. The comparison of the data from the two flights was thus able to resolve some questions about the charging and discharging capabilities of the rocket engine.

Figure 4-5 shows the electrostatic potential of the rockets as a function of altitude. Comparison of these data with that of a Boeing 707 shows some similarities and some important differences. Both rockets do not begin to charge until the rocket plume leaves the ground. The effective conductive length of the plume is about 650 feet. On the other hand, the 707 begins to charge as soon as the wheels leave the ground. Engine charging causes the potential to rise to 80 or 160 kilovolts depending on whether water injection or dry engine operation is being used. As soon as the conductive plume leaves the ground, engine charging causes both rockets to charge to high potentials. Both rockets, however, quickly discharge to below 20 kilovolts before they even reach 5000 feet.

In clear weather, the potential on the 707 decreases monotonically to zero as the altitude is increased. However, if the 707 encounters precipitation, its potential rises to a high value. The precise value (about 60 and 330 kilovolts in the two examples shown) depends on the density and type of cloud. The potential of both Titan III-C rockets also decreases to zero as the rockets climb. However, the potential of Titan III-C-21 is only slightly affected by an encounter with precipitation.

The insensitivity of the rocket potential to triboelectric charging undoubtedly stems from the high conductivity of the high-temperature rocket plume. Similar behavior is observed on fighter aircraft equipped with afterburners. In flight tests with an F-4, it was observed that operating the afterburner on takeoff increased the engine charging, thereby increasing the aircraft potential. When the aircraft was at operational altitude, however, the activation of the afterburners served to help discharge the aircraft and reduce its potential.

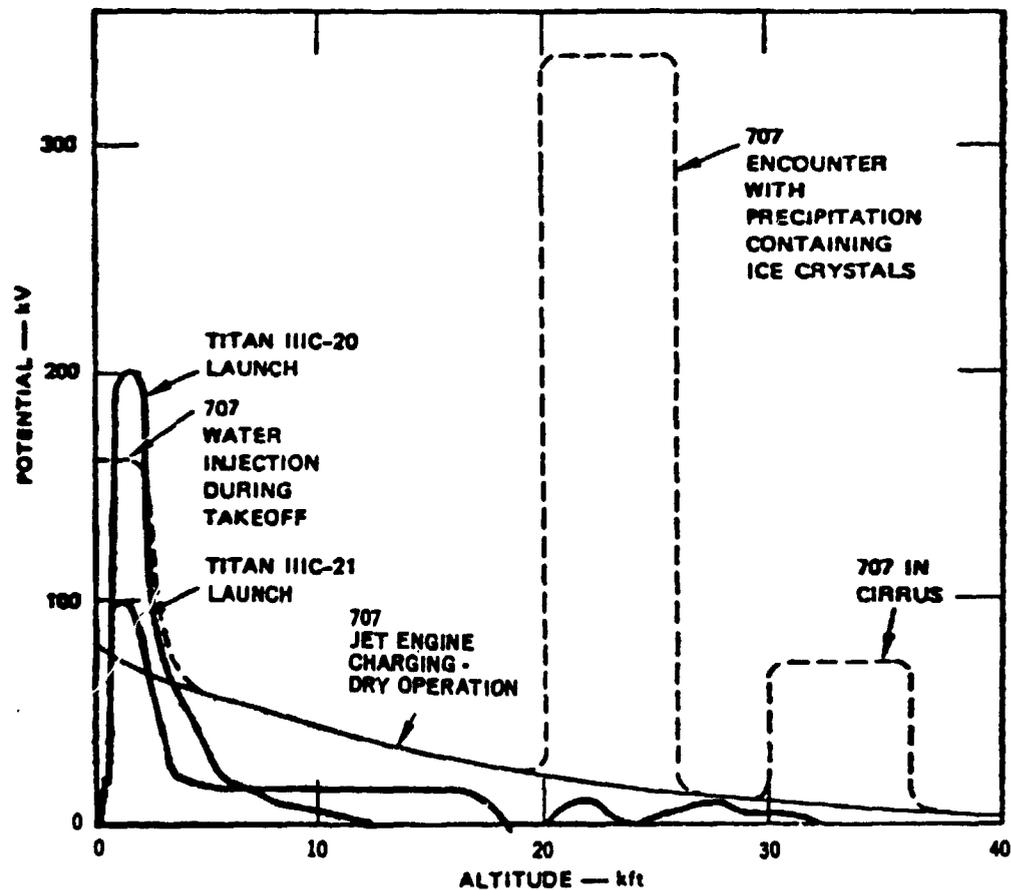


Figure 4-5.- Comparison of potential of Boeing 707 aircraft in flight and Titan III-C in launch.

During staging, all the sensors showed a high degree of activity. This indicates that the retrorockets used to push the solid rocket motors away from the Titan bathed the vehicle in exhaust products.

## 5.0

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